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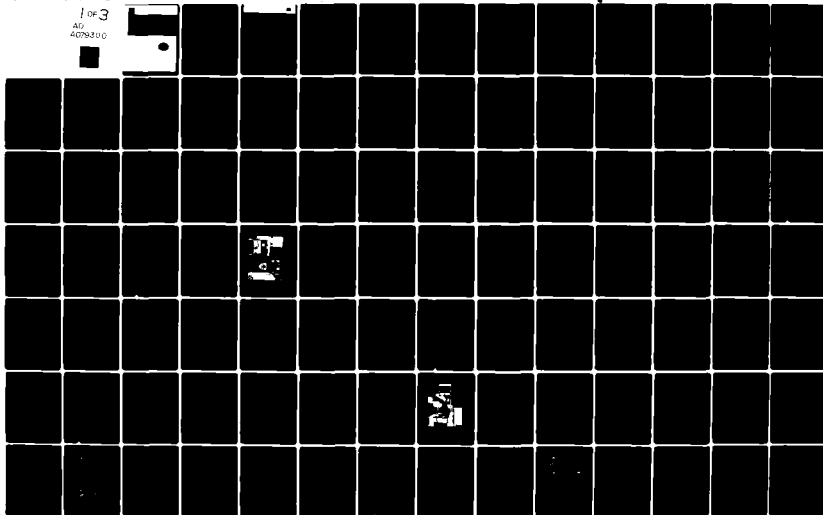
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Final Report

Covering the Period 15 September 1963 to 15 January 1965

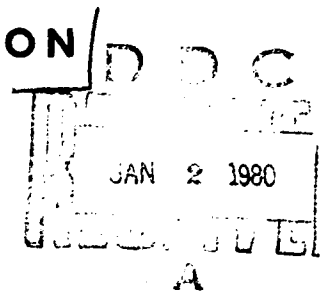
EXPERIMENTS IN TACTUAL PERCEPTION

By: JAMES C. BLISS & HEWITT D. CRANE

Prepared for:

AIR FORCE AVIONICS LABORATORY
ELECTRONIC TECHNOLOGY DIVISION
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

CONTRACT AF 33(615)-1099



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MENLO PARK, CALIFORNIA



Final Report

~~Contract AF 33(615)-1099~~ 15 September 1963 to 15 January 1965

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CONTRACT AF 33(615)-1099,

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FOREWORD

This report was prepared by Stanford Research Institute under Contracts NAS 2-1679 and AF 33(615)-1099 (Project 4160, Task 416001), with Dr. James C. Bliss as Project Leader. Contract NAS 2-1679 was monitored at the Ames Research Center, National Aeronautics and Space Administration, Moffett Field, California, by Mr. Richard Weick. Contract AF 33(615)-1099 was monitored at the Electronics Technology Division, Air Force Avionics Laboratory, Research and Technology Division, by Dr. Mildred B. Mitchell.

ABSTRACT

This report describes basic studies on tactile perception and communication. There are five main sections (II to VI) describing different psychological experiments and seven appendices describing instrumentation and equipment for these experiments.

In Section II are described experimental sessions in which words, sentences, and paragraphs were transmitted to subjects by a tactile display. Arrays of airjet and piezoelectric bimorph stimulators were programmed so that alphabetical patterns moved across these tactile displays in much the same manner as certain news display boards. Subjects were able to read tactually from these displays at a rate of 20 words per minute after less than 20 hours of training, and one subject reached 30 words per minute in 45 hours of training. Airjet and bimorph stimulators are compared, the effect of varying the size of the stimulator array is studied, and the effect of type font is discussed.

Sessions in which a specially designed tactile alphabet was developed are discussed in Section III. Factors such as learnability, edge effects, letter packing, and number of fingers used are considered. Tactually naive subjects were able to identify these letters correctly at a rate of about two random letters a second after 25 hours of practice.

In Section IV, studies of two-dimensional compensatory tracking with a continuous visual display, a discrete visual display, and a discrete tactile display are described. A series of experiments were performed with these displays in which display gain and command signal bandwidth were varied. For various values of these parameters, mean-squared error was calculated as a function of command signal delay. Performance with the tactile and discrete visual displays was found to be approximately equal. Minimum mean-squared error with both discrete displays was generally poorer than with the continuous visual display except under

low command signal bandwidth and high display gain conditions, where minimum mean-squared error was almost equal for all three displays.

A series of phenomenological observations is described in Section V. Apparent position, apparent motion, and illusions are some of the effects commented on.

Finally, in Section VI three series of quantitative studies are reported. The first is a study of the effect of deliberate stimulus pattern "jitter" on performance. It is found that a small circular translation of the stimulator array can improve performance for letter transmission, and an empirical relation among performance, frequency of stimulus pattern rotation, and stimulus presentation time is determined. Next, a study concerned with methods of tactually transmitting the magnitude of a single analog parameter is described. Information analyses are used to compare various presentation techniques. Third, the theory of signal detection is applied to a study of the human observer's ability to discriminate among different loci of tactual stimulation.

In the appendices, details of the construction of airjet and piezoelectric tactile stimulators are given, the digital-computer-controlled instrumentation system and associated computer programs are described, and equipment for tactile tracking is described.

CONTENTS

FOREWORD	
ABSTRACT	iii
LIST OF ILLUSTRATIONS.	ix
LIST OF TABLES	xiii
GLOSSARY OF TERMS	xv
ACKNOWLEDGMENTS	xix
I INTRODUCTION	1
A. Background	1
B. Present Program	6
C. Tactile Stimulators	7
D. Experiments	8
II TACTILE READING OF TEXTUAL INFORMATION	13
A. Introduction	13
B. Subjects	17
C. Stimulation Conditions	17
D. Training Sessions	20
E. Exploratory Experiments	34
F. Reading-Rate Determinations	36
G. The Effect of Array Width	37
H. Discussion	38
III SPECIALLY DESIGNED ALPHABET	43
A. Developing an Alphabet	43
1. Comments on the Alphabet Set	47
2. Modifications from Second-Subject Training	48
B. Training Tactually Naive Subjects	51
C. Discussion	58

CONTENTS (Continued)

IV	TACTILE TRACKING EXPERIMENTS	59
	A. Introduction	59
	B. Effect of Display Gain with Low Command Frequencies . .	61
	C. Experiments Including Higher-Frequency Command Signals .	64
	D. Improvement of Response by Training	67
	E. Error Evaluation with Delay	69
	F. Discussion	81
V	PHENOMENOLOGICAL OBSERVATIONS	85
	A. Modes of Presentation	85
	B. Apparent Position	89
	C. Losing Corners	90
	D. Apparent Motion	91
	E. Three-Dimensional Apparent-Motion Effects	92
	F. Repetitive Presentation	93
	G. Illusions	94
	H. Ambiguity and Learning	95
	I. Selective Perception	96
	J. Discussion	96
VI	QUANTITATIVE STUDIES	97
	A. Introduction	97
	B. Effect of Stimulus Pattern Movement	98
	1. Experiment 1--Exploratory	100
	2. Experiment 2--Learning and Response Factors	102
	a. Sessions 1-21	102
	b. Sessions 22-23	109
	c. Sessions 24-25	110
	d. Sessions 26-35	111
	e. Sessions 36-53	112
	3. Experiment 3--Effect of Stimulus Pattern rpm and Stimulus Duration Time	115
	4. Experiment 4--Effect of Amplitude of Stimulus Pattern Movement	121
	5. Discussion	123

CONTENTS (Concluded)

C.	Estimation of Stimulus Position and Physical Length of Stimulus Pattern	124
1.	Experimental Arrangement	124
2.	Procedure	124
3.	Experimental Results	126
4.	Discussion	129
D.	Signal Detection Theory Approach to Two-Point Discrimination	130
1.	Procedure	131
a.	ABX Experiment	131
b.	Same-Different Experiment--Binary Choice . . .	132
c.	Same-Different Experiment--Rating Scale	132
2.	Results	133
3.	Discussion	138
VII	OVERALL PLANS AND DISCUSSION	139
	BIBLIOGRAPHY	145
APPENDICES		
A	Airjet Array 1	149
B	Airjet Array 2	155
C	Bimorph Array	161
D	Digital-Computer-Controlled System	165
E	Computer Programs	175
F	Tracking System 1	183
G	Tracking System 2	191

ILLUSTRATIONS

Figure	Page
II- 1 Concept of Dynamic Embosser	15
II- 2 Circuit Arrangements of Photocell, Resistor, and Lead Zirconate Reed (Bimorph)	16
II- 3 Finger Stimulation with the Bimorph Array	19
II- 4 Block Letter Alphabet	21
II- 5 Braille Symbols	23
II- 6 Typewriter Font	25
II- 7 Blind Subject Reading Tactually	28
II- 8 Effect of Presentation Rate on Reading Rate	31
II- 9 Textual Reading Performance Curves	32
II-10 Performance Curve of Correct Random Letter Rate vs Session	34
II-11 Reading Accuracy vs Number of Columns	39
III- 1 Position of Airjet Array for Studies of Tactile Reading	44
III- 2 Experimentally Developed Alphabet	45
III- 3 Modified Version of Experimentally Developed Alphabet .	53
III- 4 Accuracy (Percentage of Correct Responses) and Rate (Correct Letters Per Second) by Session for Subject S4	56
III- 5 Confusion Matrix for Sessions 18 through 20, Subject S4	57
IV- 1 Experimental Arrangement for Two-Dimensional Tactile Tracking	60
IV- 2 Analog Computer Program for Each Coordinate in the Initial Compensatory Tracking Experiments	61
IV- 3 Performance vs Display Gain for Commands Composed of 0.05, 0.01, and 0.2 cps	62
IV- 4 Typical Command and Integral Squared Error Signals . .	63
IV- 5 Analog Computer Program for Compensatory Tracking Experiments Using Prerecorded Command Signals	64

ILLUSTRATIONS (Continued)

Figure		Page
IV- 6	Performance vs Display Gain for Three Filter Corner Frequencies	65
IV- 7	Performance vs Filter Corner Frequency for Display Gain of 25	66
IV- 8	Effect of Training on Performance	68
IV- 9	Analog Computer Program for Experiments Using the Delay Generator	70
IV-10	X-Axis Performance as a Function of Command-Signal Delay for Various Display Gains and Command-Sig... l Bandwidths	73
IV-11	Y-Axis Performance as a Function of Command-Signal Delay	75
IV-12	Typical Y-Axis Responses	77
IV-13	Minimum Mean-Squared Error vs Display Gain	78
IV-14	Minimum Mean-Squared Error vs Command-Signal Bandwidth .	79
IV-15	Integral Squared Error vs Time	80
IV-16	Error with and without Delayed Command	81
V- 1	Stimulus Patterns	86
V- 2	Sketched Responses to Patterns A and B	90
V- 3	Sketched Responses to Patterns D and E	90
V- 4	Sketched Responses to Pattern F	91
V- 5	Sketched Responses Showing Effect of Apparent Motion . .	92
V- 6	Stimulation for Volumetric Perception	93
V- 7	Sketched Responses to Pattern H	94
V- 8	Sketched Response to Pattern J	94
V- 9	Initial Sketched Responses to Pattern I	95
V-10	Initial Sketched Responses to Pattern J	95
V-11	Initial Sketched Responses to Pattern M	96
VI- 1	Test Scores for Each Session	105
VI- 2	Average of Test Scores for Each Session	107
VI- 3	Effect of Stimulus Presentation Time on Performance . .	114
VI- 4	Performance as a Function of rpm	117
VI- 5	Performance as a Function of Stimulus Presentation Time	118

ILLUSTRATIONS (Continued)

Figure		Page
VI- 6	Effect of Amplitude of Circular Translation of Stimulus Array on Recognition of Blocked Letters	122
VI- 7	d' vs Separation between Stimulators for the ABX Experiment	134
VI- 8	Percent Correct vs Separation between Stimulators for ABX Experiment	135
VI- 9	ROC Curves	136
VII- 1	Overall Program Schematic	141
A- 1	Electromagnetic Air Valve	152
A- 2	Relaxation Oscillator Circuit for the Electromagnetic Air Valve	153
A- 3	Air Pressure Measured 1/8 Inch Above Airjet Stimulator 1 (2.5 msec/cm)	153
A- 4	Interior of Tactile Display Consisting of 96 Airjet Stimulators	154
A- 5	Tactile Display Unit	154
B- 1	Airjet Tactile Stimulator	157
B- 2	Output Air Pressure Pulses for Airjet Stimulator 2	158
B- 3	Exploded View of One Row of Airjet Matrix	159
B- 4	1-by-8 Airjet Stimulator Array	160
C- 1	12-by-8 Bimorph Stimulator Array	164
C- 2	Physical Arrangement of a Bimorph Stimulator	164
D- 1	Block Diagram of Digital-Computer-Controlled System	167
D- 2	Control Logic	168
D- 3	Drive Circuitry for Air Vibrators--Single Element	171
D- 4	Synchronous Airjet Stimulation System	172
D- 5	Timing Mode 1	174
D- 6	Timing Mode 2	174
E- 1	Flow Diagram for "Times Square" Computer Program	179
E- 2	Flow Diagram for a "Times Square" Display of Closely Spaced 7-by-8 Patterns	180
E- 3	Flow Chart for Computer Programs	182

ILLUSTRATIONS (Concluded)

Figure		Page
F- 1	Block Diagram of Circuitry for Tracking Experiment	186
F- 2	Amplitude Gate Circuitry	188
G- 1	System for Two-Dimensional Tracking	194
G- 2	Zones Illustrating the Operation of the Two-Dimensional Ring Tracking Display	195
G- 3	Single-Axis Mode for System of Fig. G-1	196

TABLES

Table		Page
II- 1	Stimulus Conditions	27
II- 2	Reading Material	33
II- 3	S3 "Goodness" Judgments on Stimulation Produced by Various Pulse Widths and Pulse Intervals	36
IV- 1	Display Gain for Various Combinations of DC Display Gain and Command Signal Bandwidth	71
IV- 2	Minimum Mean Squared Error with the Discrete Displays .	82
VI- 1	Subjective Reports on Various Conditions of Stimulus Pattern Movement	101
VI- 2	Protocol for Stimulus Movement Experiments	103
VI- 3	Analysis of Variance for Sessions 36-53	113
VI- 4	Data from Stimulus Movement Experiment 3 for S9	117
VI- 5	Analysis of Variance for Experiment 3	118
VI- 6	Treatment Effects	119
VI- 7	Data from Stimulus Movement Experiment 3 for S10 . . .	120
VI- 8	Transmitted Information	126
VI- 9	Comparison of Two Locations for Tactile Stimulation . .	127
VI-10	Comparison of Performance for Various Stimulus Conditions	127

GLOSSARY OF TERMS

Airjet Array 1

This is the original airjet array, based on the use of mechanical flapper valves. The details of design and performance are discussed in Appendix I.

Airjet Array 2

This is a second version of airjet array based on the use of magnetically driven steel balls which serve as valves. The main purpose of this design was to reduce the amount of air leakage when the valve was closed (the flapper valves were marginal in this respect) and also to enable operation of the jets at a higher frequency.

Bimorph Array

This is an array of elements, each consisting of a sandwich of two layers of oppositely polarized electrostrictive material that bends upon application of a voltage. The same drive circuits can be used for the airjet and bimorph arrays. In one case the electrical signals operate valves to control air flow, and in the second the electrical signals control mechanical vibration. Because the bimorph array must be brought into contact with the skin, it is more difficult to use over a wide area of skin than the airjet array.

Synchronous-Asynchronous Drive Systems for the Stimulator Arrays

It is found that good sensation is achieved with a frequency of stimulation in the 100- to 200-cps range. Thus, when a stimulator is said to be energized, what is meant is that the stimulator (airjet or bimorph) oscillates at a certain frequency for as long as the stimulator is left "on." Initially, the 12-times-8, or 96, oscillator circuits were unsynchronized, although they were all

adjusted to oscillate at about the same frequency. With some modification it was possible to synchronize all of the oscillators.

Frame Presentation

In this mode the entire pattern is stored in the interface equipment, and then all jets are turned on simultaneously.

Times Square Pattern Scan 1

In Times Square display mode a pattern is introduced on one edge of the display and continues to move along the display a frame at a time until the pattern runs off the other edge. The Times Square mode is then essentially a series of frame presentations with the pattern shifted appropriately between frames. In the Times Square 1 mode the 8-by-12 array is oriented to be eight rows high with the pattern progressing along the 12 columns.

Times Square Pattern Scan 2

In this mode the 8-by-12 array is turned 90 degrees so that the display is 12 rows high and the pattern progresses along the 8 columns.

Single and Double Jump

This refers to the manner in which the pattern progresses in either Times-Square mode. With single jump, the pattern moves one column at a time. With double jump the pattern moves two columns with each successive presentation.

Masking

This refers to a programming technique in which the effective width of the array can be controlled by entry of a key number in the program. With a visual Times Square display, masking would correspond to controlling the width of the window through which viewing takes place.

Line Scan

In this mode of presentation a given pattern is displayed a single line at a time from top to bottom. There is further facility to

control the number of lines displayed at any instant. Thus, as each new line is energized, a row an arbitrary number of positions n back can be erased, or de-energized. For $n = 1$, only a single line at a time is presented, the previous line being erased as the next line is energized.

Point Scan

This routine displays the pattern one point at a time according to the following sequence (1,1), (2,1), ..., (7,1), (8,1) then (1,2), etc. The first number indicates the row and the second number indicates the column of the pattern matrix.

Start-Stop and Backup Control

These refer to switches which the subject can use to stop or start the display program, or to cause the display program to back up a number of letters in the sequence.

Space Bar

In a sequence of letters, a space bar is a blank field equal in width and presentation time to a letter.

Block Letters

These are relatively conventional block letters without serifs.

Typewriter Font

These are letters derived from quantizing standard pica typewriter letters.

Braille I Symbols

These are "dot" stimuli on a 2-by-3 matrix corresponding to the Braille code for the letters of the alphabet.

Specially Designed Alphabet

This is a set of alphabetic shapes designed for tactual perception and to resemble conventional letters as much as possible.

DC Display Gain

This is the ratio of output to input for the tracking display.

Normalized Display Gain

This gain is the ratio of the maximum possible command signal for a given command signal spectrum, to the full scale signal on the tracking display.

Command Signal Bandwidth

In some of the tracking experiments, the command signal was filtered by a simple lag whose corner frequency defines the command signal bandwidth.

Apparent Motion

This phenomenon is observed when two stimulators are activated in time sequence, and the perception is as though one stimulator moved from the position of the first to the position of the second.

Apparent Position

This phenomenon is observed when two stimulators are activated simultaneously and the perception is as though one stimulator were activated at some intermediate position.

Stimulator Array Movement or "Jitter"

In this mode, the entire array of airjet nozzles is circularly translated at a fixed rpm and amplitude.

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While the authors are responsible for the material contained in this report, certain sections are primarily the work of others and are so indicated. In addition, we would like to acknowledge the contributions of J. Eige and P. Newgard, who designed the airjet stimulators; K. Gardiner, who designed circuits in the digital computer interface equipment and the tracking equipment; B. Lane and T. Ferrera, who conducted many of the experiments involving subjects; F. Clarke, who helped plan the initial tracking experiments and performed experiments related to the application of signal detection theory; H. Seeley, who contributed his analysis of tracking error data with delay; C. Rice, who helped design the special alphabet; K. Kotovsky, who conducted some of the first experiments on pattern movement; and S. Link, who planned and analyzed the pattern movement experiments involving analysis of variance.

I INTRODUCTION

Apart from its use by the visually handicapped, the tactile system has not generally received serious consideration as a method of communication. However, with the advent of complex man-machine systems, it is becoming more important to study all potential methods of communication between man and his hardware systems. In this regard, the tactile system deserves serious attention, for the sense of touch is certainly capable of receiving information at high rates, as evidenced by the deaf-blind, who by placing their fingers on the lips, jaw, and throat of a speaker can receive live speech in real time.

The use of a high-speed computer to generate and control rapidly changing tactile patterns has opened up new areas in tactile research, research that will be important for the development of tactile communication systems. Hence, the development of a computer-centered experimental facility was an integral part of the project reported herein. The status of this facility is summarized in the appendices.

The results of the tactile perception studies performed in connection with the experimental facility are discussed in the body of this report. To provide a background for these studies, a brief summary of some previous research is given below.

A. Background

There has, of course, always been deep interest in the tactile sense, since in almost every activity the tactile receptors in our skin serve to inform us of the world around us. Tabori (1962) and Révész (1958) have compiled interesting information about the physical aspects of touch, especially about the function of the hand, and Burton and Kantor (1964) have discussed some modern research on the emotional factors involved in touch. As for experimental research, it has been broad and diverse. The following is a very brief summary of the areas of research relevant to this report, and a reference or two has been given for each area of study,

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though it should be borne in mind that the amount of material available on each area is extensive.

The tactual system, quite simply, consists of receptors in the skin, innervated by peripheral nerves from the dorsal roots of the spinal cord. These fibers form relatively distinct tracts in the spinal cord, synapsing in the midbrain and in the thalamus, with subsequent fanning out to various regions of the cortex. Montagna (1956) discusses the structure of the skin and the anatomy of the neural endings. There is extensive controversy over the nature of the nerve endings. Von Frey's ideas of "specific nerve energies," implying distinct nerve endings for each modality, such as touch, pain, hot, cold, pressure, and tickle, cannot be confirmed. Some comments from Weddell (1961, page 16) may convey the gist of the controversy.

"In the hairy skin of man (apart from the back of the fingers) I soon found that only (and this has been confirmed many times now) two morphologically distinct types of nerve terminals could be found under the light microscope; those ending in relation to hairs and so-called 'free' nerve endings, which were present at all levels in the skin...The 'free' nerve endings are diffuse, widespread arborizations, arising sometimes from large myelinated fibres, but more usually from fine myelinated and non-myelinated axons, leaving the cutaneous plexus. Hairy skin covers well over 90 percent of the body surface. Even parts that do not appear to be hairy contain numerous fine down-like hairs which are often lavishly innervated, for example, the skin covering the ears....Where then are Krause end-bulbs and other complex nerve endings end-formations to be found? Surprisingly, they are only found in exposed mucous membranes and in the hairless skin of the hands and feet. Meissner corpuscles in the hairless skin of the hands and feet take the place of hairs in hairy skin. Some of the end-organs in exposed mucous membranes undoubtedly transduce tactile stimuli, others may transduce thermal stimuli, but this is as yet unknown. Despite this, reports of touch, warmth, cold, and pain can all be evoked with relative ease from the hairy skin of the face, the mucous membrane of the lip and the skin covering the fingers and hands. The only terminals common to all types of skin are the so-called "free" nerve-endings and one is forced to the conclusion that in hairy skin, at least, it is these endings which must serve the modalities of warmth, cold and pain...."

From a somewhat different point of view, Mountcastle (1961, page 88) comments:

"...and I know he (Weddell) agrees with me that even though the peripheral endings of sensory fibers innervating the hairy skin appear similar when examined in stained sections through the light microscope, we must not conclude that they are all functionally equivalent.... The large majority of both myelinated and unmyelinated fibers are modality specific...Most of us have ideas of our own, then, concerning the degree of specificity of first order afferent fibers, ideas prejudiced by our own experiments, perhaps. To me a very important point is that in the central reaches of the somatic system specificity is exquisitely preserved--and this could hardly occur if this lemniscal component (commented on further below) were fed by first order fibers equally sensitive to all forms of impinging energy."

Wyburn (1960, chapter 3) schematically summarizes the neuroanatomy of the tactual system, tracing the tracts through the spinal cord to the cortex. Less distinct than the ascending and descending tracts through the spinal cord are the systems of collaterals and synaptic connections which occur at every vertical level. For one discussion of these collateral systems see Wall (1960). Because of the vast expanse of the tactual system one does not encounter the tactual equivalent of complete blindness or deafness, though of course there can be specific areas of tactual loss through specific damage. There appear to be two major systems of taction which provide safety factors against complete tactual loss. These two systems are discussed by Mountcastle (1961) in the following selections from the referenced work:

"That the two major afferent systems concerned with somatic sensibility are not functional duplicates is a fact long established in clinical neurology....I shall draw data firstly from experiments on what I shall call the lemniscal system....This system preserves in a most specific way those properties of the stimulus which are subsumed under the terms of local sign and modality specificity. It is organized in a powerful way to accentuate ground contrast and to follow rapid transient alterations in the locale or the temporal pattern of the peripheral stimulus, qualities which I suppose are described as adequately by the word epicritic as by the

one I have chosen. The lemniscal system consists minimally of a portion of the myelinated dorsal root afferents, the dorsal column nuclei, the thalamic ventrobasal complex and the postcentral gyrus." (p. 68).

"It (the lemniscal system) is a system of precise anatomical connections, although over and above its anatomical specificity--even here there is considerable divergence--there are physiological attributes which tune it for discriminatory functions as precise as any known in nature. Among these attributes are temporal facilitation and afferent inhibition, and doubtless there are others yet to be discovered." (p. 81).

"The other...system I shall term the anterolateral. It is composed of dorsal root fibers, dorsal horn cells and their upwardly projecting fibers in the anterolateral columns of the cord, the posterior nuclear complex of the thalamus, and the second somatic area of the cortex. The functional properties of this system are on almost every count different from those of the lemniscal. Within it there is spatial convergence to such a degree that modality specificity is lost." (p. 68).

"Hunt and Kuno found them to be activated from rather large receptive fields, which often include more than one limb and which may be bilateral in distribution. Although the majority are sensitive to mechanical stimulation of peripheral tissues, many discharge only when the stimulus is one injurious to tissue. Lastly, there is certainly evidence that this system is involved in that afferent activity which leads to the perception of pain.... There is evidence of a considerable cross convergence between the two systems, at both the thalamic and cortical levels." (p. 81).

Mountcastle (1957) also discusses the organization of the somatic cortex. He shows data that

"...support an hypothesis of the functional organization of the cortical area. This is that the neurons which lie in narrow vertical columns, or cylinders, extending from layer II to layer VI make up an elementary unit of organization, for they are activated by stimulation of the same single class of peripheral receptors, from almost identical receptive fields, at latencies which are not significantly different for the cells of the various layers." (p. 408).

In addition to the neurophysiological studies, there have been rather extensive psychophysical studies of tactual perception. These studies have primarily been limited to the effects produced by a single

stimulus, or at most a few stimuli, at a time. There have also been extensive studies on the mapping of the skin according to different modalities, studies which were often accompanied by attempts to correlate specific sensitivity with the underlying anatomy, in particular, ending types. Rothman (1954, chapter 5) discusses some of the results of such studies and comments on warm spots, cold spots, itch spots, and so on.

Other studies have been limited to a single stimulus technique in an effort to correlate subjective sensation with the many parameters of stimulation. For example, von Békésy carried on extensive tactile vibration studies simultaneously with audition studies and was very successful in predicting and proving many auditory phenomena on the basis of analogous tactile phenomena. Perhaps the best introduction to the extensive literature in this field is von Békésy's book on hearing (von Békésy, 1960). In this work, von Békésy discusses many phenomena of importance for the development of systems involving tactual communication, such as (1) spatial interaction of a pair of adjacent stimulators leading to "apparent position" effects and lateral inhibition models; (2) temporal effects relating to the perception of vibratory pitch, in particular, the sensitivity of pitch perception to vibratory amplitude; (3) sensitivity to waveshape and the great difference between click excitation and sinusoidal excitation; (4) spatial-temporal effects leading to "apparent motion" effects and "rotating sounds," the latter being strongly analogous to a similar auditory phenomenon (5) similar effects from a number of different stimulation modes, such as thermal and electrical, in addition to vibratory; and (6) interaction of modes, e.g., a rotating sensation between a thermal stimulator and a vibratory stimulator.

The psychophysical experiments noted above involve subjective responses only. Other studies involve electrical recording of responses, either by surface electrodes [e.g., Uttall (1959) recorded responses by placing surface electrodes on the forearms] or by surgically implanted electrodes. The latter studies have usually been conducted on animals, although Hensel and Boman (1960) report on one study in which human responses were recorded by electrodes surgically implanted in the forearm.

Extensive studies using embedded electrodes have been made at the spinal-cord level (Wall, 1960) and at the central level (Mountcastle, 1957). In these studies, recordings are made in response to stimulation at some point of the periphery.

As useful and important as these single-electrode studies are, to develop more complete models of the tactile system it is also necessary to study responses to more complex stimulus patterns. However, until recently, no technological equipment like that used in making sophisticated auditory and visual experiments was developed for tactual study. The high-speed computer has now provided the means of making comprehensive, flexible tactual experiments. Also, electronic technology has now progressed to the point where it is feasible to place relatively large arrays of tactile stimulators in a small space.

B. Present Program

A relatively large part of our program to date, especially during the first year, has been devoted to the development of a tactile research facility to provide greater ease, flexibility, and reproducibility of complex spatial-temporal tactile stimulation. With this facility we have the capability of conducting an extensive psychophysics program based on complex stimulation patterns rather than on the relatively simple patterns available with just a few stimulators.

Ideally, to understand the tactual system we have to know all the parameters of every stimulus pattern to which the system can respond. However, much of this information would be irrelevant to our goal of tactile communication. For example, by the time we were able to transmit tactual patterns, we would find that there is a relatively wide range of amplitudes, just as in vision and audition, over which there is relatively small effect on the data transmission rate. Therefore, we have felt that it would be unwise to take what might appear to be the most methodical approach of studying each parameter in turn. (This statement is not intended to defend the somewhat ad hoc approach we have taken, but rather to explain it.) Thus, we have conducted experiments in a number of different areas simultaneously and have altered the approach

as experimental results dictated. For our present purposes, these experiments will be divided into two broad categories; (1) those concerned with actual data transmission for communication and control, and (2) those concerned with more basic psychophysical studies.

The long-range goal of the program can be thought of as the development of a functional model for the tactile sense. A comprehensive model should (1) permit predictions of human information acquisition capabilities to be made with any potential display, (2) describe in terms of the unknown physiology the information processing that occurs with tactile inputs, and (3) answer in what ways the tactile modality compares with other sense modalities. Knowledge of the last would permit us to perform certain tactile experiments to simulate functions now performed with other sensory systems. (Thus, von Békésy was able to predict certain features of the auditory system by making certain tactile experiments.) In any case, our choice of experiments has also been influenced by a desire to obtain information that could be useful in developing models.

C. Tactile Stimulators

Stimulation of the tactile sense can be accomplished with electrical, mechanical, thermal, and chemical stimuli. For communication, the most practical methods are probably mechanical and electrical. Although there has been some recent advance in "painless" electrical stimulation (Gibson, 1963), this means may be impractical where a large number of electrical stimulators are required, since each stimulator might have to be carefully adjusted. Of the mechanical stimulators, airjets give a strong sensation and, because they are noncontacting, are relatively easy to position and adjust. Another important advantage of airjet stimulation in a spatial array of stimulators is that relatively uniform stimulation can be achieved over non-uniform cutaneous surfaces. In his discussion of cortical responses of neurons related to cutaneous receptors, Mountcastle (1957, page 409) comments:

"...about 60 percent of all neurons of the cutaneous group were activated by stimulation of the hairs. Such units are exquisitely sensitive to bending of the hairs of the skin--so much so that they are optimally driven by short weak jets of air delivered against the hairs."

Airjet stimulation of the skin has been used by many investigators. For example, Allen and Hollenberg (1924) measured the critical frequency of fusion for air pulses and found that it increased with pressure. Allen and Weinberg (1925) report that the critical fusion frequency for airjet stimulation can also be increased somewhat by simultaneously stimulating a nearby region. Bellows (1936) also measured cutaneous flicker fusion frequency with airjet stimuli and showed that it decreased with the duration of stimulation. Most recently, Saslow (1962) investigated thresholds, magnitude scales, and information transmission using a 3-by-3 matrix of airjets, and Kotovsky and Bliss (1963) have reported on apparent location, spatial acuity, apparent motion, and temporal acuity with airjet stimulation.

Stimulators powered by piezoelectric bimorphs have also been used in our experiments. These are much quieter and consume much less power than the airjet stimulators. The characteristics of piezoelectric bimorph transducers are described by Lion (1959, page 78), and their use as tactile stimulators is described in Alonzo (1964). Piezoelectric bimorphs have been used by Agalides (1963) for direct stimulation of tactile receptors isolated from their surrounding tissue. Since the motion produced is similar to that produced by mechanical transducers, results similar to those reported by other investigators working on mechanical stimulation should be expected.

D. Experiments

One reason for the interest in developing techniques of information transfer via the tactual system is, of course, to provide the blind or deaf-blind with a substitute for their sensory loss. The availability of computers has made possible the development of systems in which vast amounts of data, stored in a computer, are readily available to a blind

user via a proper output transducer. In fact, through the development of a readily usable visual-to-tactual translator, it appears possible to give the blind access to any written material.

To determine the actual usefulness of such a sensory translation device, we have used our experimental computer system to generate English text and have converted this text into tactual output. The results of studies of this type, using blind subjects, have been very encouraging. With meaningful text, we have reached relatively quickly a rate of about 30 words per minute. The studies made to date with these blind subjects are discussed in Section II.*

The alphabet used with the blind subjects, in the experiments noted above, was simply a version of capital English letters. It was noted that when using the airjet stimulators, the subjects had difficulty with these letters, which were relatively complex in structure, so that they sometimes sensed only an unstructured blast of air. It then became apparent that simply by reducing the structure of the letters, i.e., by reducing the number of stimulator points, subjects could learn to recognize these "abstracted" letters with great accuracy and also with considerable speed. Several sighted subjects have now been trained on this improved alphabet, and reading rates of about two random letters a second have been readily achieved. These results are described in Section III.† However, no tests were made with contextual material prepared in this alphabet to determine word rates; to date, the work with sighted subjects has been largely confined to experiments in modes of presentation.

Experiments have been made to determine the effect of varying the position of the displayed characters in time in a predetermined way, namely, by rotating the entire two-dimensional array in a circular translation mode. The results of these experiments, described in Section VI,† indicate that a significant improvement in subject performance is obtained in this way.

* These studies were carried out under a National Institute of Health grant.

† Supported under Contract AF33(615)-1099.

Also described in Section VI* are two other quantitative studies. The first explored various methods of tactually presenting the magnitude of an analog quantity, and an informational analysis was made to compare the methods. Anatomical landmarks were found to be a very important factor in tactile localization, and an information-per-presentation comparable to single-dimension visual and auditory stimuli was obtained. In the second study, signal detection theory was applied to tactile localization. Values of d' (a measure of the ability of an observer to distinguish between a pair of stimuli) were determined for various distances between the stimuli.

Preceding these quantitative studies is a discussion of a number of phenomenological observations (Section V†).

Another type of information transfer experiment that involves spatial-temporal response is tactile tracking. From visual tracking experiments, many important parameters that describe the human transfer function in this task have been determined, and it would be useful to determine whether these parameters are essentially the same with tactile input. For example, considerable experience has been gained from experiments in which a subject is asked to move a control stick in accordance with the movement of a light. It is interesting to consider use of the tactual system for such control (e.g., for control of a vehicle) when it is desirable to release the visual system for other activity, or when the visual system cannot function because of, say, very high vibration and g-stress.

The results of some preliminary comparative studies of this type are discussed in Section IV.* It has been found, for example, that the performances of a subject given discrete tactual stimuli and a subject given discrete visual stimuli are generally similar, though the performance with both of these discrete displays is poorer than when a continuous

* Supported under Contract NAS 2-1679.

† Supported under Contract AF 33(615)-1099.

visual display is used. Such comparative studies should further the understanding of human responses to a tracking situation and should be useful for determining which functions may be treated as common and which are specific to a given sensory mode.

II TACTILE READING OF TEXTUAL MATERIAL

A. Introduction

This section describes experimental sessions in which words, sentences, and paragraphs were transmitted to subjects by tactile means. The objectives of these experiments were to determine what information rates are possible with simple tactile coding and to explore the practicality of some possible applications of this type of display.

In the past, many tactile languages have been developed and used, primarily for the blind. Farrell (1950) describes the development of symbol sets such as Moon Type, Haüy's embossed letters, and Braille. Methods such as these for coding letters of the alphabet into tactile symbols can be classified as follows:

- (1) Codes in which the tactile symbols are exact or modified copies of their visual counterparts. Embossed letters and Moon type are examples of this type of code.
- (2) Codes in which the tactile symbols bear little or no relation to the standard printed alphabetic shapes. Braille is an example of this type of code.

The practical advantages of the first group over the second are that less learning is required and much simpler equipment can be used to produce the tactile images from optical alphabetic shapes. From a research standpoint, the shorter learning time allows information-rate measurements to be made sooner, and the similarity to visual patterns permits investigation of the transfer of learned visual images to corresponding tactual images.

Studies of the ability of subjects to distinguish static embossed letters have been conducted by Austin and Sleight (1952) and Dinnerstein and Wolfe (1962). Austin and Sleight found that 0.5-inch-high embossed letters of masonite could be recognized in about 3.5 seconds if the subject were allowed to move his finger over the embossed letters. Dinnerstein and Wolfe allowed their subjects to explore the letters only through a narrow slit. They found that 3.5-inch-high letters cut

from chenille could be tactually recognized with about 90-percent accuracy at a rate of about one letter every 3.6 seconds.

Examples of tactile codes not related to alphabetic shapes are given in the studies of Geldard (1957) and Bliss (1962). Geldard studied a code that used 5 stimulator locations, 3 intensities of stimulation, and 3 durations of stimulation to give 45 combinations, 26 of which represented the letters of the alphabet. He reported that after 16 hours of training, a subject could receive information at a 35-wpm rate. Bliss studied a code consisting of passive finger movements similar to those used in typing. He found that subjects could achieve an information rate of 4.5 bits per second* after 15 hours of training. By comparison, Grade II Braille can be read at well over 100 wpm, but a complex code with 185 English contractions is involved.

The sessions described in this section were almost all devoted to tactile reading of alphabetic shapes. This special case of tactile communication has an important application as a possible method of giving the blind access to the printed page. Using the equipment and computer programs previously developed, we have had the opportunity to investigate this special case under National Institutes of Health sponsorship.

For many years research efforts have been directed toward finding a means, operable by a blind person, of translating material on a printed page directly into a form comprehensible without vision. A novel scheme to produce a dynamically embossed facsimile of ordinary

* For a random sequence of the 26 letters of the alphabet, in which the letters are statistically independent and equally probable, each letter has an information content of $\log_2 26 = 4.7$ bits. Thus, a rate of 4.7 bits per second corresponds to one random letter per second. However, English text contains considerable redundancy, so that each letter in context may actually transmit only about one bit of information on the average. Taking this redundancy into account, there is about a 10-to-1 ratio between words per minute and bits per second. Thus, 4.7 bits per second corresponds to about 47 words per minute. Experiments surveyed by Attneave (1959) indicate that well trained subjects tend to process information at a constant information rate rather than a constant letter rate when sequential constraints (redundancy) between letters are varied.

printing for tactual reading has been reported by Linvill (1964) and studied further by Alonzo (1964). As in many systems proposed in the past, images are translated into a corresponding pattern of pins within an array, which produces a tactile image corresponding to the black-and-white pattern on the page (see Fig. II-1).

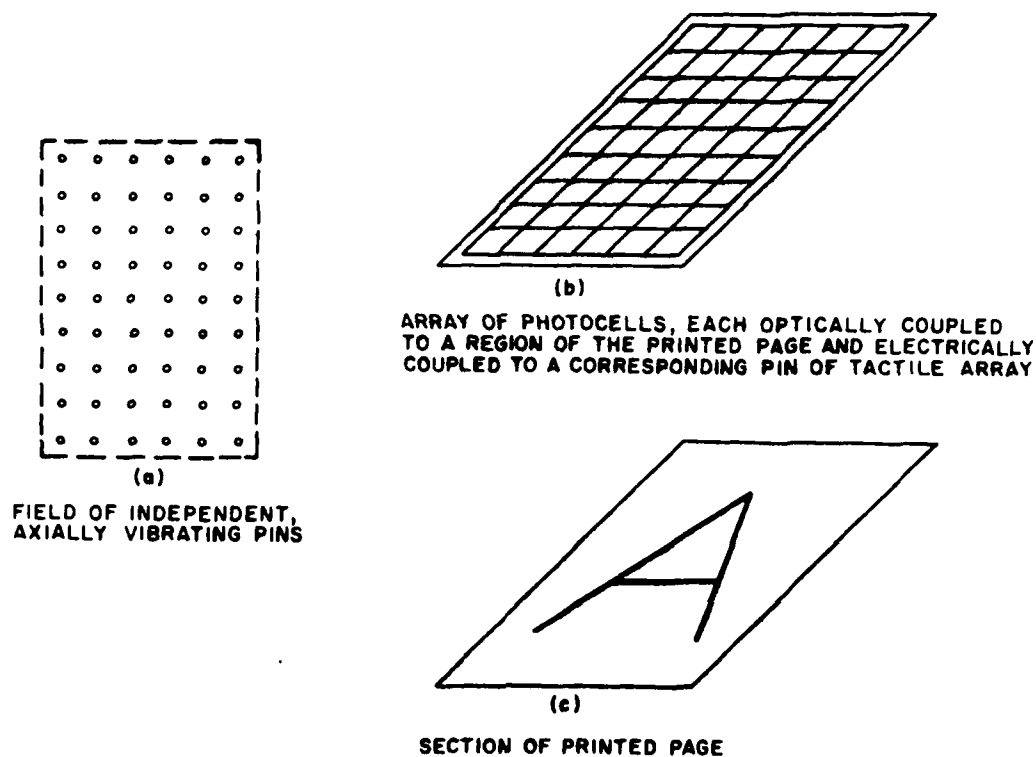
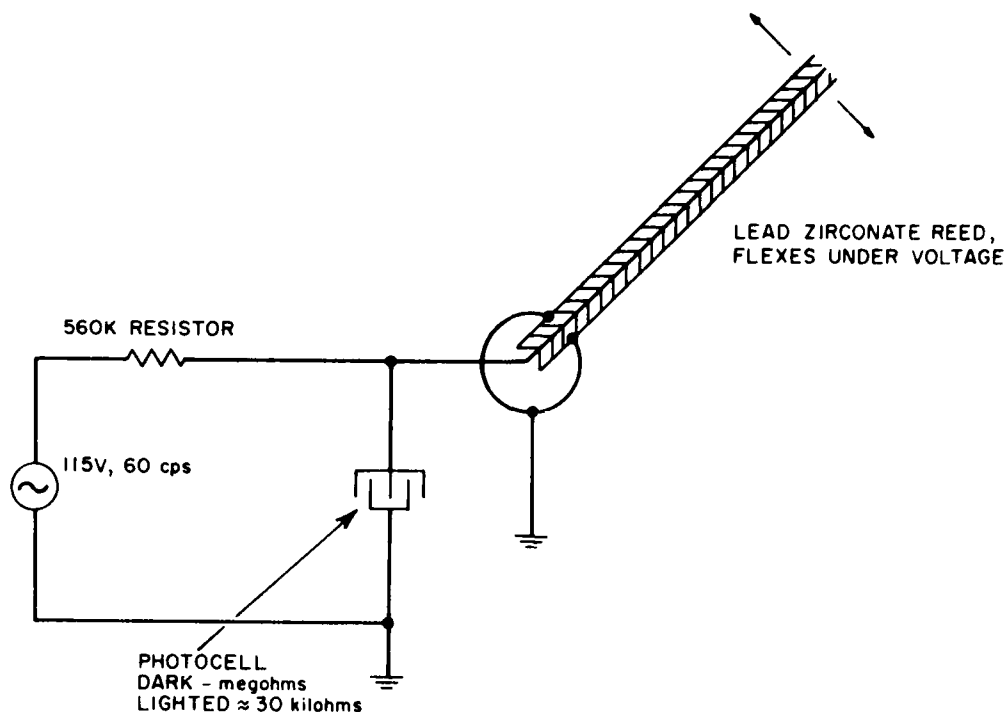


FIG. II-1 CONCEPT OF DYNAMIC EMOSSER

BA-4719-20

The unique feature of this scheme is the method of operating the pins by means of piezoelectric bimorphs coupled to photocells. Figure II-2 shows how each pin in the array can be operated. When light falls on the photocell, its resistance decreases (to about 30K), so that the bimorph is essentially shorted out and does not vibrate. When the photocell is dark, its resistance is many megohms, and the bimorph can vibrate.



RA-4719-21

FIG. II-2 CIRCUIT ARRANGEMENT OF PHOTOCELL, RESISTOR, AND LEAD ZIRCONATE REED (BIMORPH)

This extremely simple circuit realized in integrated circuit form permits the construction of a very simple and compact hand-held device that contains the photocell and vibrating pin arrays. This device could be manually scanned over printed text and an enlarged version of the print sensed tactually. Such a device, if convenient to use, would be a highly significant aid to certain blind individuals. Other applications could undoubtedly be found in situations where spatial pattern perception is needed but vision cannot be used.

Instead of using a simple direct-conversion optical scanner as an input device, a computer can be used as a primary source of material and may be practical for other types of applications as well as for the blind. For example, navigation information in alphanumeric form could be taken directly from a computer output and transmitted to an astronaut without the use of visual or auditory channels. In this situation it

might be appropriate to build the tactile display into the suit or helmet (for example, the cheek is a relatively large sensitive surface and the helmet is a convenient rigid surface on which to mount tactile stimulators). Also, with the computer industry striving to make computer time less expensive and perhaps available by the simple lifting of a telephone receiver, it may be that the terminal equipment necessary to convert control signals from a central computer would be inexpensive enough to make a central computer facility attractive as a library source for the blind. This kind of computer control would permit considerable flexibility in the programming, so that possibilities for perusal, scanning, and variations in reading rates could be included in the program.

B. Subjects

The three subjects used in the reading sessions are briefly discussed below.

S3: Our initial subject was a 12-year-old girl who is in the seventh grade at a regular school. She is an avid Braille reader. Reading sections from an article in the Saturday Evening Post, she scored 76 words per minute on a Braille I reading test and 125 words per minute on a Braille II reading test.

She has been blind since she was about 8 months old and totally blind since she was about two years old.

S11: This subject was a 16-year-old boy, a senior in a regular high school. He reads Braille II every day and can read at about 100 wpm.

He went blind gradually and could read and see colors until he was 10 years old. He has had no light perception for three or four years.

S13: This subject was an 18-year-old sophomore girl at Stanford University. She reads Braille II every day and has read as fast as 137 words per minute.

She was blind from birth and never had any light perception.

C. Stimulation Conditions

Two types of tactile stimulation were used in the sessions discussed in this section. The majority of sessions were conducted with the

12-by-8 array of piezoelectric bimorph stimulators described in Appendix C. A few sessions were performed with one of the two arrays of airjet stimulators described in Appendices A and B. Airjet stimulators 1 (described in Appendix A) were initially used because construction of the bimorph array had not been completed. When both types of stimulator arrays were available, the sessions were usually conducted with the bimorph array, except for an occasional session with one of the airjet arrays for comparison.

While the three subjects had much more practice with the bimorph stimulators, they expressed no strong preferences for one type of stimulation over the other. Initially S13 preferred the airjets, but once the bimorphs were adjusted to her liking, this preference disappeared. However, the two types of stimulation differ physically and psychologically in several ways.

The bimorph stimulators are considerably less noisy than the airjets, and the pin that contacts the skin is smaller than the cross section of the airjet. In addition, the bimorph array has a sensing plate on which the subjects pressed their fingers (in both normal and tangential directions) to allow the pins to contact the skin through the perforations in the sensing plate. The airjets had no equivalent of a sensing plate; the subjects merely held their fingers about 1/4 inch above the nozzles. Since the bimorphs are mounted at a 45-degree angle to the sensing plate, the pin motion was both normal and tangential to the skin surface, while the airjets were all pointed vertically. Compared with the bimorphs, the airjet stimulators are capable of more intense stimulation, and, for research purposes, their spacing is more easily changed. Also, in contrast to the bimorph stimulators, the airjets produce uniform stimulation over a nonuniform cutaneous surface because skin contact is always made. For example, a typical report is that a horizontal line, moved across the bimorph array by the Times Square Program and sensed with two or three fingers, is lost between the fingers and perceived as "dashed." However, with the airjet stimulators, the same horizontal line is perceived as continuous.

The sensation from the bimorph stimulators is described as a very localized vibration, almost a tickle. The airjet stimulation is described as softer and more comfortable.

In all cases the stimulation was on the fingers. Subject 3 used either her left index finger or left middle finger, and S11 used his left index finger. Subject 13 used her right index finger. The finger used generally corresponded to the way the subjects read Braille. Figure II-3 shows how the finger was placed with respect to the bimorph array. The reading rates were generally sufficiently fast that active finger movements were useless for scanning a letter, and the subjects always kept their finger in a stationary position.

Several methods were used to activate the tactile stimulators during the course of the sessions. Initially, with S3, the airjet and bimorph stimulators were each activated by a separate relaxation oscillator (see Appendix D), which resulted in airpulses at about 70 cps and in an

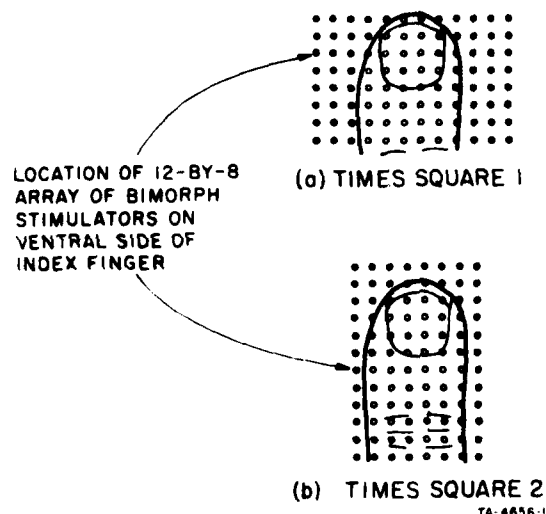


FIG. II-3 FINGER STIMULATION
WITH THE BIMORPH ARRAY

asynchronous-patterned stimulation. Later, a synchronous stimulator drive system was substituted (see Appendix D), with the airjet stimulators being driven at 200 cps and the bimorph stimulators at 250 cps. (A lower frequency was required for the airjet stimulators because they cannot operate reliably at 250 cps.)

Also, two Times Square programs were used. In one program, the letters were moved from right to left along the long (12 stimulators) dimension of the array, and in the other program, the letters were moved from right to left along the short (8 stimulators) dimension of the array.

Most sessions were conducted using the standard block letters shown in Fig. II-4. A few exploratory sessions have been conducted with Braille symbols, as shown in Fig. II-5. Subject 3 is now learning the typewriter font shown in Fig. II-6, which was obtained by quantizing standard pica type on a 7-by-8 grid.

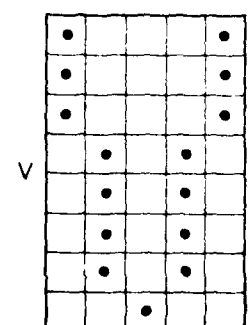
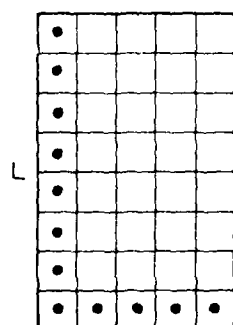
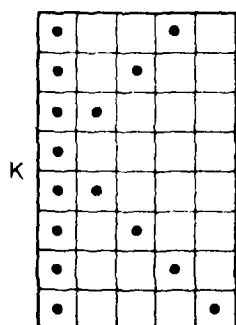
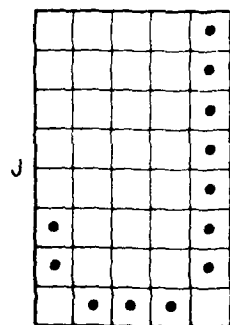
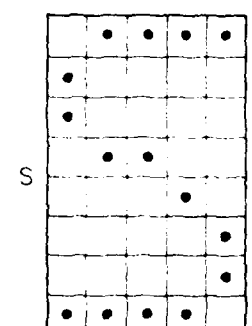
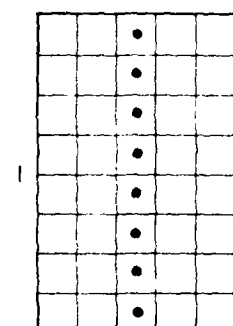
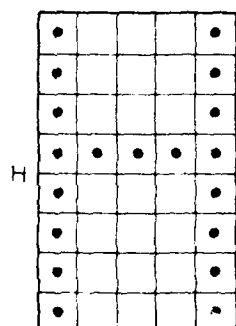
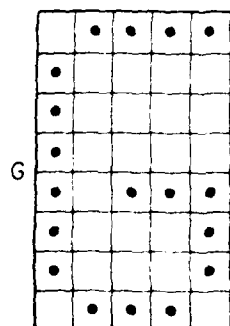
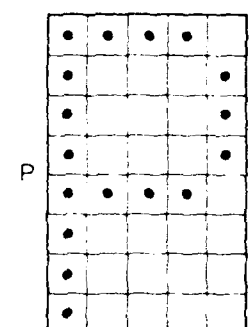
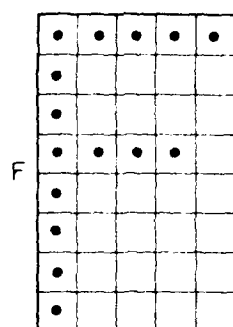
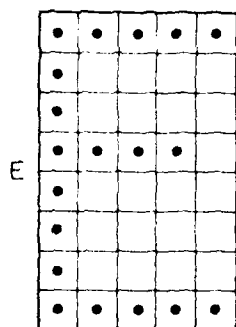
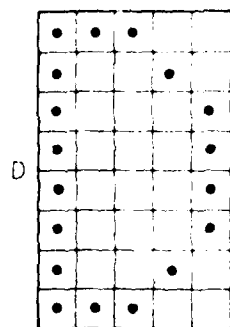
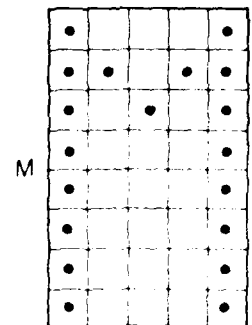
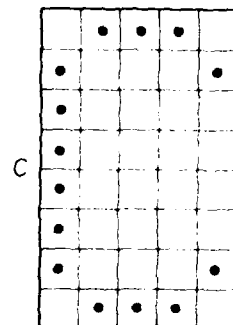
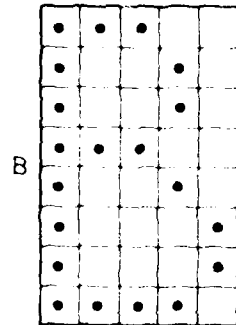
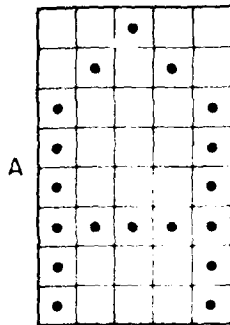
Table II-1 summarizes the conditions for the sessions, and Fig. II-7 shows a subject reading tactually.

D. Training Sessions

The initial training sessions with each subject were relatively informal and flexible. Our objectives were (1) to determine if text, coded into a dynamic tactile presentation of alphabetic shapes, could be read at all, and (2) to investigate the relative importance of various display parameters using trained subjects. Thus, we were more interested in getting the subjects to a relatively high reading rate than in finding out precisely how long the training period is and what the specific characteristics of the learning phase are. To illustrate how these sessions have been carried out, the experimenter's comments are recorded at the end of the first seven sessions with S3.

1. Session 1

For the first part of the session, individual letters of the alphabet were presented. The subject was not previously familiar with a number of the alphabetic shapes, even their names. Four lists of about



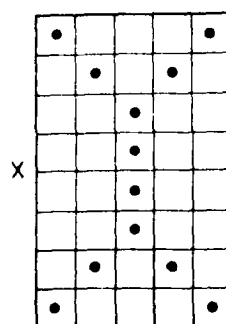
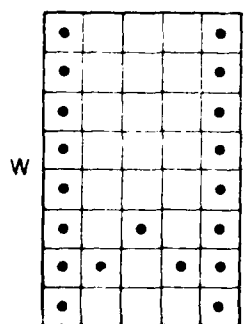
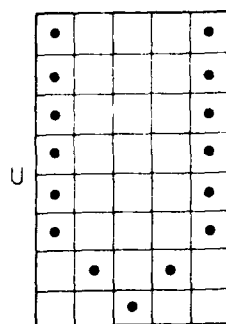
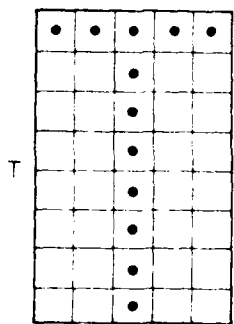
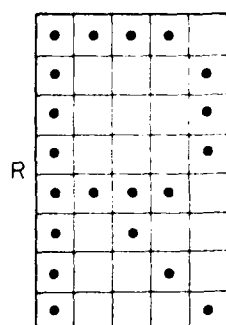
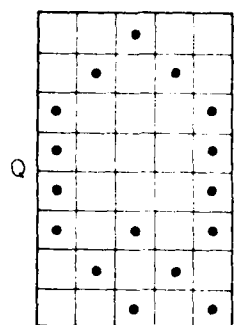
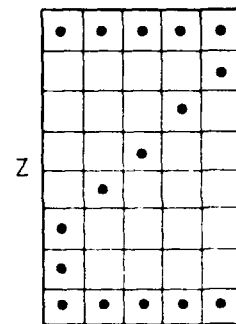
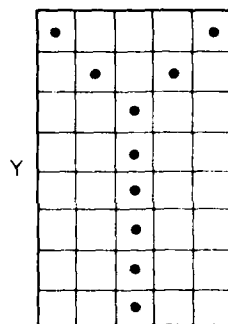
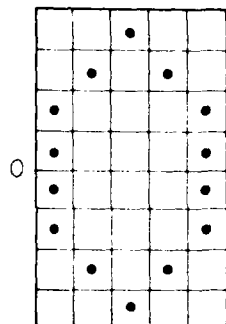
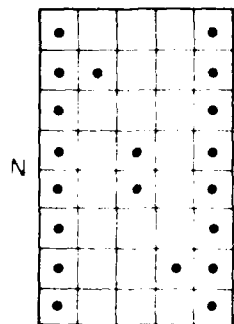
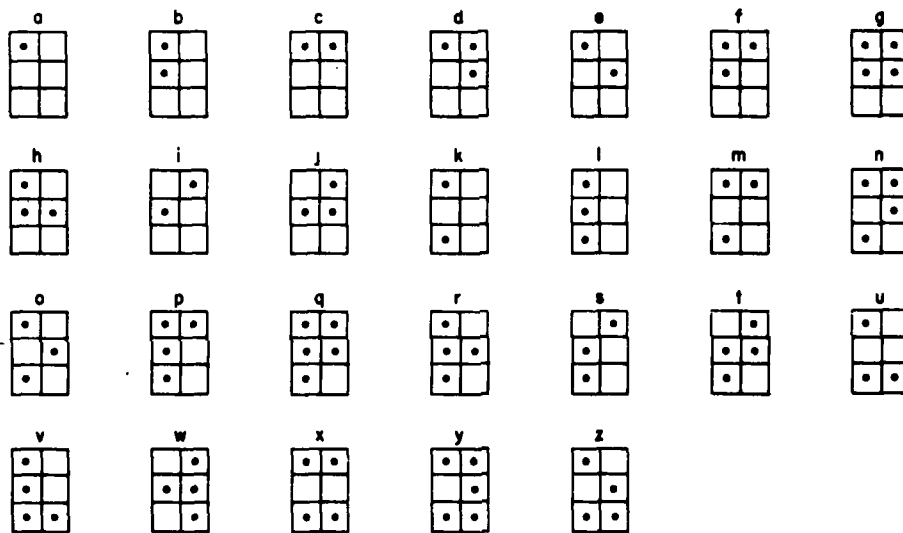


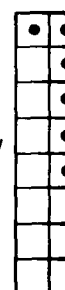
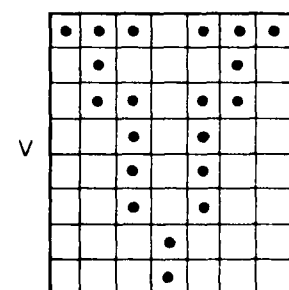
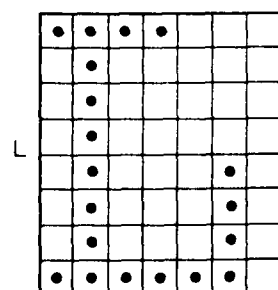
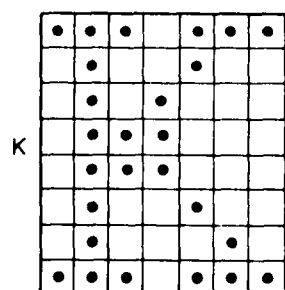
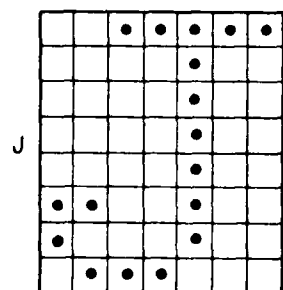
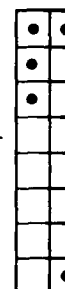
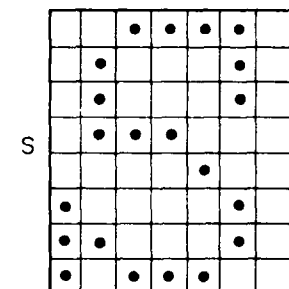
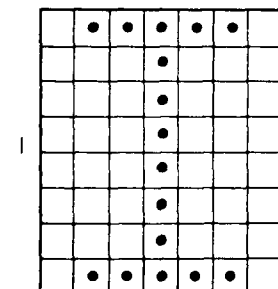
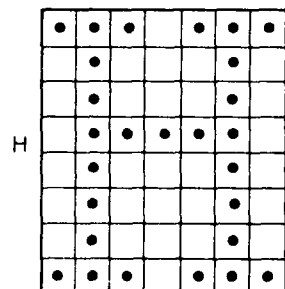
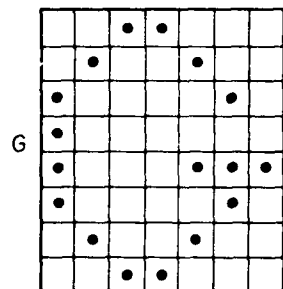
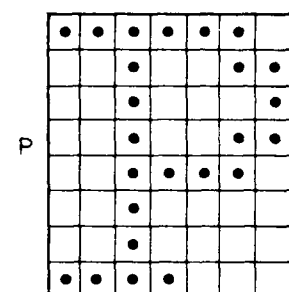
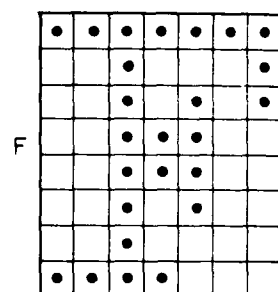
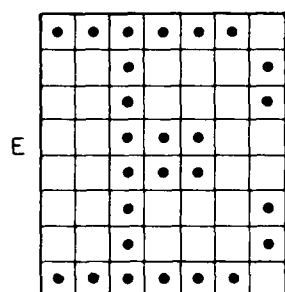
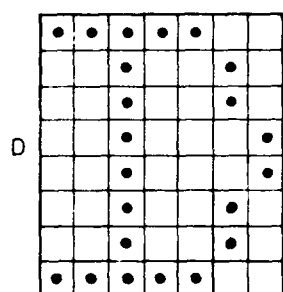
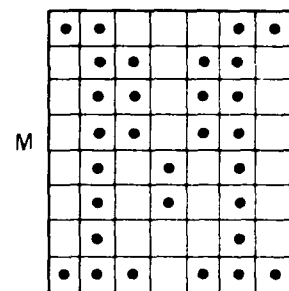
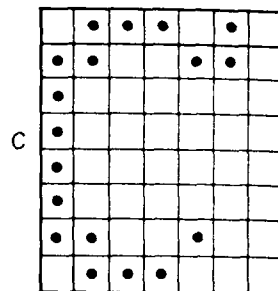
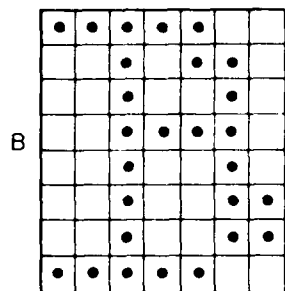
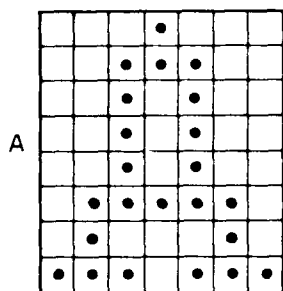
FIG. II-4 BLOCK LETTER ALPHABET

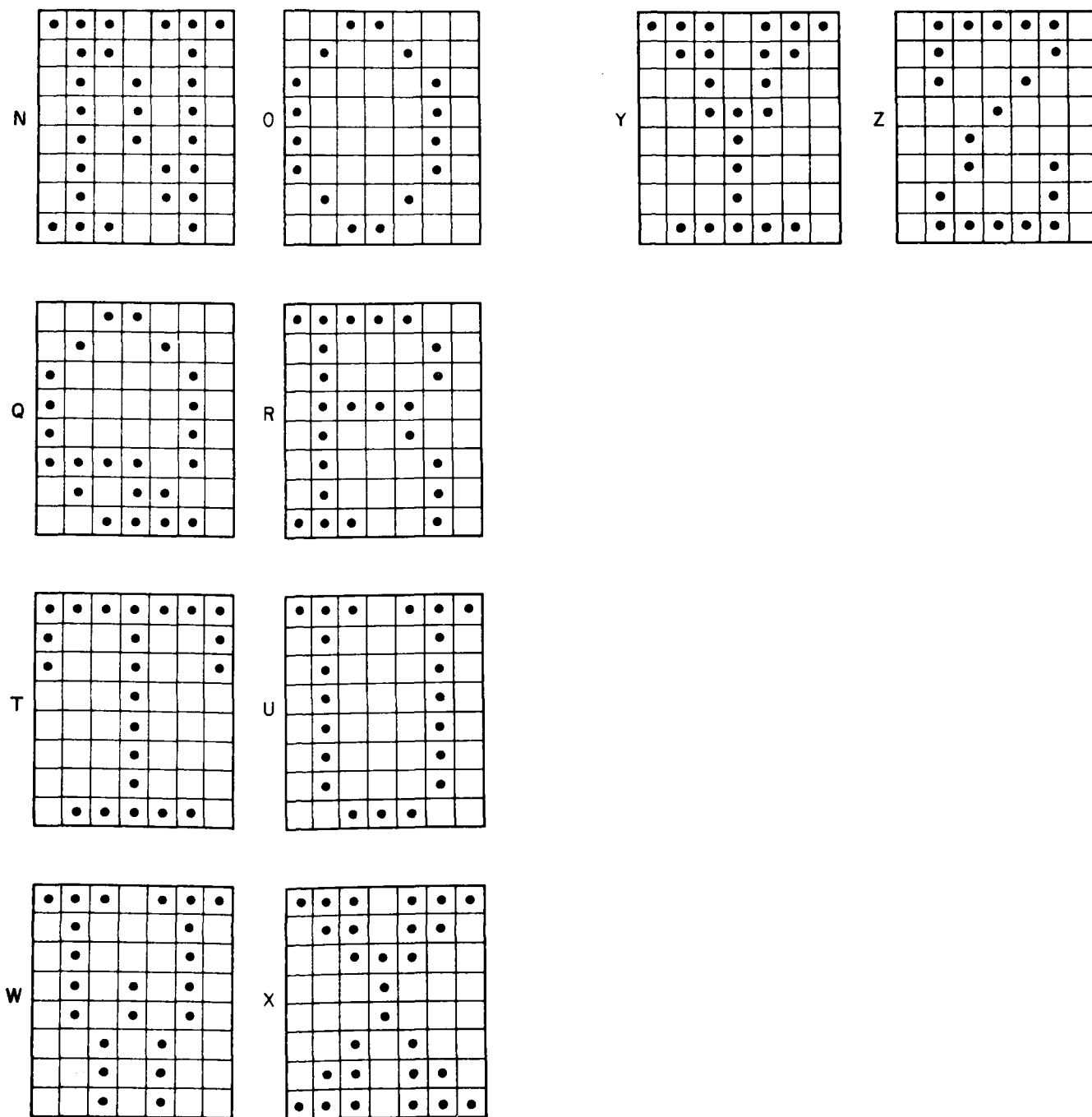
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TA-4656-2

FIG. II-5 BRAILLE SYMBOLS





TD-4656-3

FIG. II-6 TYPEWRITER FONT

Table II-1
STIMULUS CONDITIONS

Sub- ject	Session No.	Stimulator						Comments
		Type	Drive System	Freq. (cps)	Pulse Interval (msec)	Pulse Dur. (msec)	Computer Program	
S3	1-9, 19	Airjets 1	Asynchronous	~ 70	~ 14.3	~ 2	Times Square Program 1	1. Air Pressure: 10 psi 2. From Session 3 on, subject had start-stop switch. 3. From Session 6 on, subject had back-up switch. 4. Double-jump mode used on some runs in Sessions 8, 16-21, 25, and 27. 5. Braille 1 presented in Sessions 12 and 14.
	10-18; 20-22	Bimorphs	Asynchronous	~ 70	~ 14.3	~ 2		
	23, 24	Bimorphs	Synchronous	160	6.3	1		
	25, 26	Bimorphs	Synchronous	312	3.2	1		
	27	Bimorphs	Synchronous	Varied	Varied	Varied		
S3	28-37	Bimorphs	Synchronous	250	4.0	1-2	Times Square 1	Program automatically masked off all but 1-4 columns as appropriate for the column experiment.
S3	38-52	Bimorphs	Synchronous	250	4.0	1-2	Times Square 1	Equipment and programs were modified for increased duty cycle and computer control of word rate (see Appendix D).
S3	53-60	Bimorphs	Synchronous	250	4.0	1-2	Times Square 2	S3 read typewriter font; S11 and S13 read block-letter font.
S3	57	Airjets 2	Synchronous	200	5.0	~ 2	Times Square 2	Only 48 airjet stimulators were used.

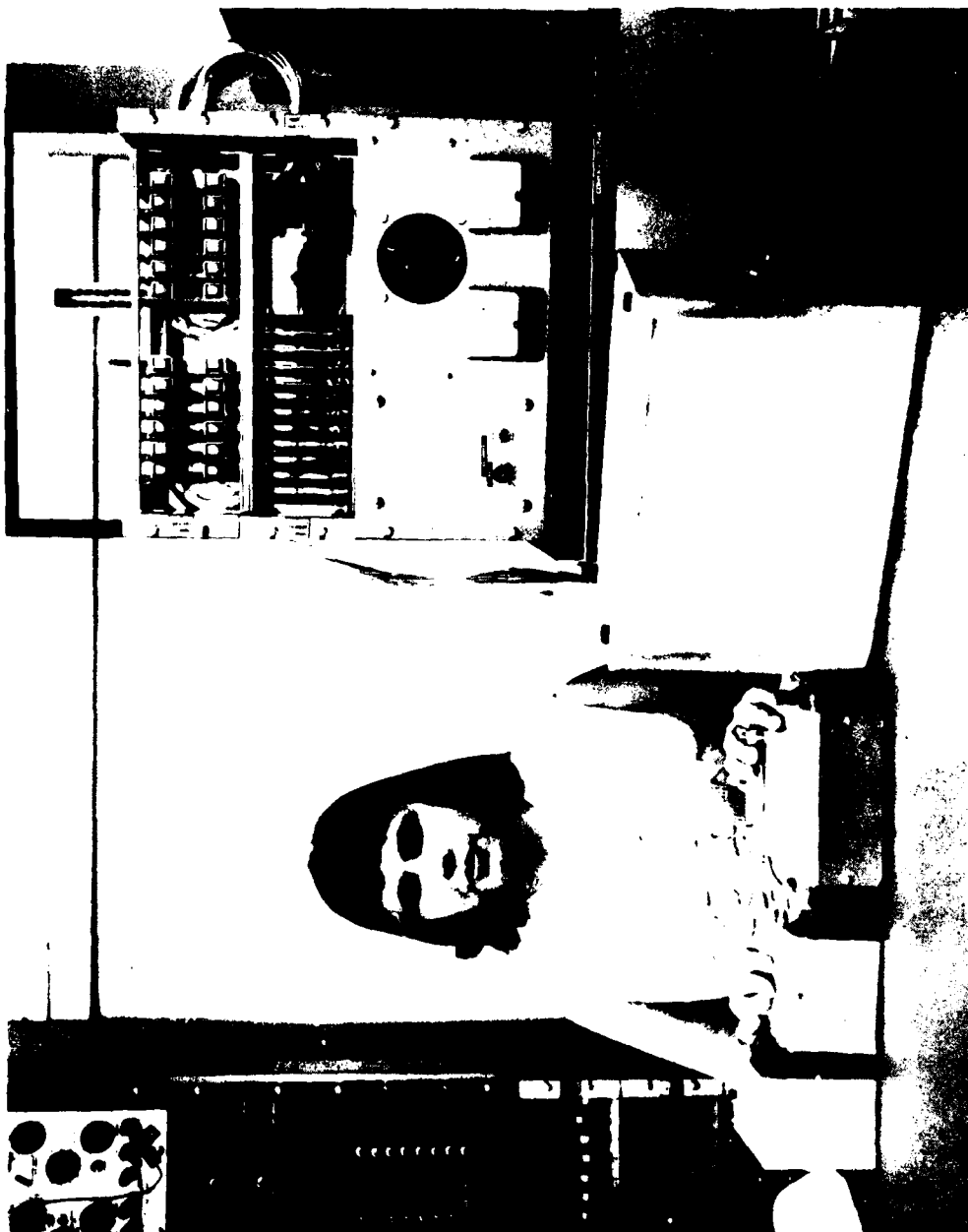


FIG. II-7 BLIND SUBJECT READING TACTUALLY

12 one-, two-, three-, and four-letter words were then presented, each about three times. Then 14 sentences were presented using the same words at two or three different speeds. Some sentences were repeated. The subject had some difficulty with the four-letter words. Not all of the sentences were read perfectly.

In the sentences there were two space bars (i.e., 14 empty columns) between words. The word rate was estimated to be 5 wpm.

2. Session 2

Augmented lists of one-, two-, three-, and four-letter words were presented, plus 20 sentences. Because of an equipment malfunction, the letters in this session were redesigned to be seven instead of eight rows in height. The subject identified most of the sentences correctly. The procedure required that the subject speak each word as she read it and that she be corrected immediately if she missed a word so that the entire sentence would not be lost.

Eleven of the sentences had three space bars between words, nine had two space bars, and one had a single space bar. No difference in readability was noticed.

The word rate was estimated to be 7 wpm, assuming an average of five-letter words plus two space bars between words.

3. Session 3

Lists of four-letter and longer words were given once each. Most words were identified correctly, the four-letter words perfectly. Three paragraphs of about five sentences each were then presented. The words ranged from one to seven letters, and the word and sentence spacings were the same as in normal typewritten text.

The air pressure at this session was 10 psi. In previous sessions an air pressure of about 3 psi was used, but the subject thought 10 psi was preferable.

The estimated reading rate for the sentences was 13 wpm.

4. Session 4

A list of five- to nine-letter words was presented once. Of the 29 words, 20 were correctly identified (of the nine words missed, two had Q's, which is a letter the subject had not learned).

Four stanzas from the poem "Clipper Ships and Captains"* were presented at a rate of 12 wpm. Approximately four words per stanza (out of 25 words per stanza) were incorrectly identified or not identified at all. Apparently the start-stop switch which left the airjet array on when the program was stopped confused the subject. (In subsequent sessions the start-stop switch operation was modified to turn the airjet array off.)

Two more poems were presented; then stanzas 1 and 2 of "Clipper Ships and Captains," were given again at 17 words per minute. Two words were missed in the first stanza and three in the second.

* Clipper Ships and Captains, 1843-1860
by
Rosemary and Stephen Vincent Benet

There was a time before our time,
(It will not come again),
When the best ships still were wooden ships,
But the men were iron men.

...

Their cargoes were of tea and gold,
Their bows a cutting blade;
And on the poop the skippers walked,
Lords of the China trade,

The skippers with the little beard
And the New England drawl,
Who knew Hong Kong and Marblehead
And the Pole Star over all.

Stately as churches, swift as gulls,
They trod the oceans, then--
No man had seen such ships before,
And none will see again.

--From A Book of Americans by Rosemary and Stephen Vincent Benet (Holt, Rinehard and Winston, Inc., 1961).

5. Session 5

Word lists and poems were presented at rates of 13, 16, 17, 18, and 19 wpm. The subject spoke each word as she perceived it, and any mistakes were immediately corrected to preserve continuity of the material. The accuracy of the sentence reading was 96 percent at 13 wpm, 91 percent at 16 wpm, and 80 percent at 18 wpm. The results of the reading tests given are shown in Fig. II-8. The most commonly confused letters were Q and O; R, A, and K; and Y and T. (The peak value of the correct word rate from Fig. II-8, namely 13 wpm, is the entry recorded on Fig. II-9.)

6. Session 6

Word lists and text were given for practice. The word accuracy was 87 percent at 19 and 22 wpm. The most difficult letters seemed to be V, W, X, Z, J, R, Q, and G. These letters were practiced.

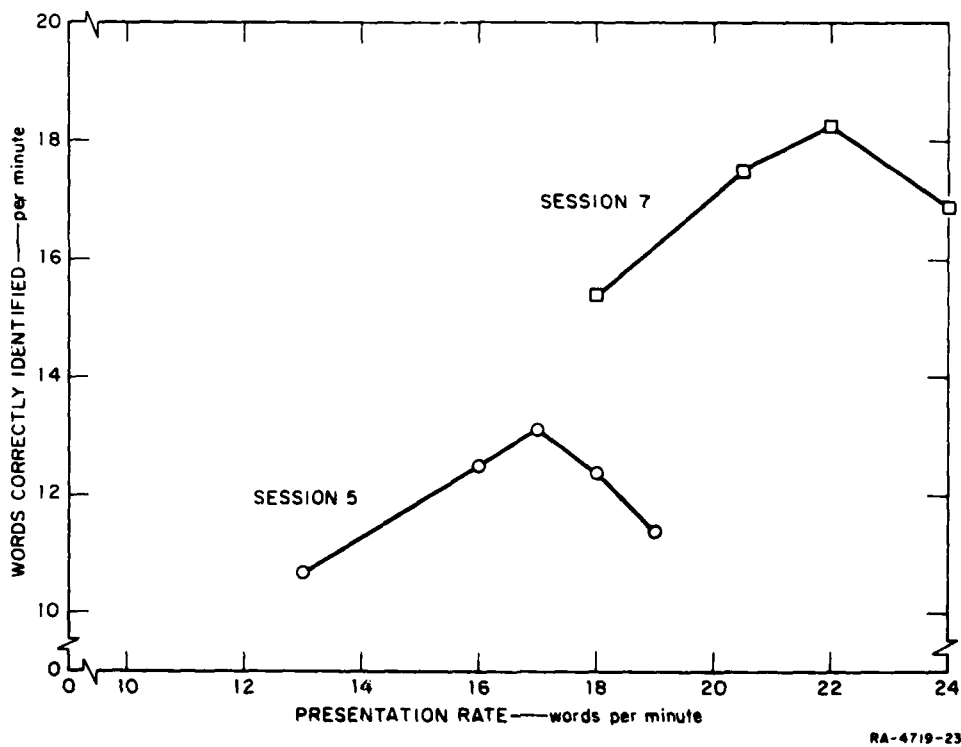


FIG. II-8 EFFECT OF PRESENTATION RATE ON READING RATE

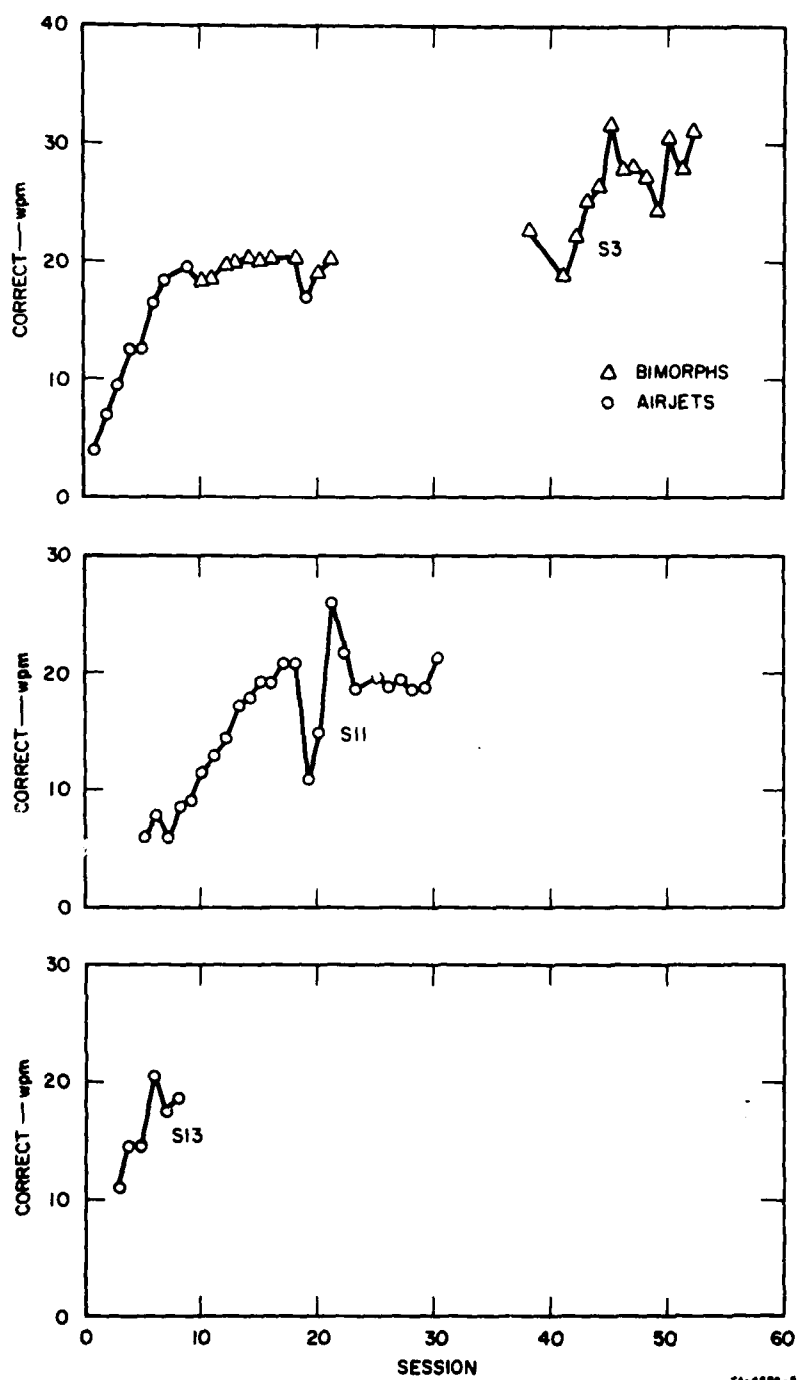


FIG. II-9 TEXTUAL READING PERFORMANCE CURVES

7. Session 7

The difficult letters from Session 6 were presented repeatedly for practice. Then a random list of letters from the entire alphabet was given at a rate such that each letter took 0.6 seconds to pass any point and there was a blank space of 1.2 seconds between letters. The subject correctly identified 50 letters of the 52 presented. Later the speed was increased to 0.4 seconds/letter and 0.8 seconds between letters, and the subject scored 49 correct letters out of 52 presented.

The subject was then asked to read several paragraphs (see Table II-2 for the material used). Figure II-10 is a plot of words correctly identified per minute as a function of the rate at which the words were presented. The air pressure was adjusted from 15 to 20 psi for these tests.

Table II-2
READING MATERIAL

Subject	Source of Material
S3	<ol style="list-style-type: none"> 1. <u>New Horizons Through Reading and Literature</u> (California State Department of Education, Sacramento, California, 1961). 2. Ian Fleming, <u>Thunderball</u> (New American Library, New York, 1962). 3. <u>The Beatle Book</u> (Lancer Books, Inc., New York, 1964). 4. <u>The True Story of the Beatles</u> (Bantam Books, Inc., New York, 1963). 5. <u>Saturday Evening Post</u>, June 20, 1964.
S11, S13	<ol style="list-style-type: none"> 1. <u>Saturday Evening Post</u>, June 20, 1964. 2. A. Huxley, <u>Brave New World</u> (Bantam Books, Inc., New York, 1955). 3. John C. Pallister, <u>The Insect World</u> (Dept. of Insects and Spiders, The American Museum of Natural History). 4. <u>Stanford Research Institute Journal</u>, No. 1, 1964. 5. <u>Reader's Digest</u>, July and October, 1964. 6. Jules Romain, <u>The Death of a Nobody</u> (New American Library, New York, 1961).

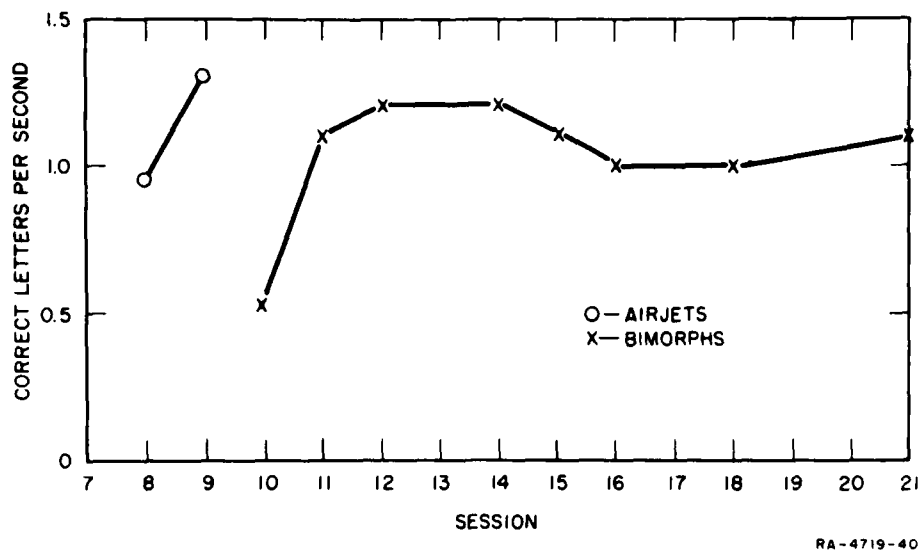


FIG. II-10 PERFORMANCE CURVE OF CORRECT RANDOM LETTER RATE VS SESSION

Similar procedures were followed with Subjects 11 and 13, except that the text material was chosen for their age and educational levels, and the letter and word spacings were kept constant.

E. Exploratory Experiments

In addition to the normally scheduled practice and test sessions, some exploratory experiments were conducted with Subject 3. Some comments concerning these informal experiments and tentative conclusions follow.

1. Sessions 12 and 14

Braille symbols consist of dots specified on a 2-wide by 3-high matrix. A natural experiment was to encode the Grade 1 Braille alphabet into Times Square Program 1 and present it to the subject. This was done very informally in Session 12 (to get an estimate of its feasibility) and more carefully in Session 14. The Braille presentation proved readable on the bimorph array, though the performance was significantly worse than with block letters (17 wpm with Braille, compared to 20 wpm with block letters). It was unreadable with the airjets. The following observations were made:

- (1) The bimorph presentation of Braille was somewhat hampered by insufficient amplitude of vibration and by small variations in the position of the sensing pins with respect to the sensing plate (both of these caused significant error, because of the lack of redundancy in Braille symbols).
- (2) The airjet display failed because the airjet spacing was abnormally large (for Braille symbols) and because the "point sensation" of Braille was lacking.

2. Session 21

Two paragraphs from "The Beatle Book" (see Table II-2) were edited to produce a text of short words only (none over seven letters), and this text was presented to the subject at the usual rate of 26 wpm. Her reading rate for this material was 23 wpm, compared with her plateau rate for normal text of 20 wpm. This result agrees with the experimenter's observation that the subject most frequently misses the longer words in a text.

Another experiment consisted in allowing the subject to "backspace" over the text using a special switch provided. The switch would cause the program to jump back a given number of letters (say seven) and present this portion again. This "backspacing" helped the subject identify some relatively difficult words, for example in the sentence "New York disk jockeys ... had been playing Beatle records as if all other performers had suddenly dropped dead," the words "playing," "suddenly," and "dead" were all missed at first but correctly identified after two or three rereadings.

Finally, a stationary mode of letter presentation was tried with the bimorph array (Frame Scan mode). Because the letters were wider than the finger tip, the subject could identify the letters if she could move her finger horizontally. If their on-time was relatively short, however, she lost enough of the letter to give a poor performance.

3. Session 27

In this session S3 was asked to rate the "goodness" of the stimulation produced by various values of pulse width and pulse interval of the bimorph drive signal. The reported judgments are given in Table II-3.

Table II-3
S3 "GOODNESS" JUDGMENTS ON STIMULATION
PRODUCED BY VARIOUS PULSE WIDTHS AND PULSE INTERVALS

Pulse Period (msec)	Pulse Widths (msec)		Comparisons Among "Best" Combinations (1 means best)
	Best	Good	
8	1.5	1	4
6.3	1.5	1	4
5.0	2.5	1.5, 2	3
4.0	2	1.5	1
3.2	1.5	1	2
2.5	1	1.5	4

On this basis, a pulse width of from 1 to 2 msec and a pulse interval of 4 msec was chosen for subsequent sessions.

4. Session 53 - 60

In these sessions S3 was taught the capital typewriter font shown in Fig. II-6. It was found that there was very little transfer from the block letters of Fig. II-4, so that the learning resembled the initial sessions with this subject. This font is obviously more difficult than the block letter font, primarily because of the serifs, which make it difficult to distinguish between such letters as B and E, F and P, U and V, and H and N. However, after these sessions, these letters could be adequately distinguished tactually so that text could be read at 10 wpm. Further practice is expected to increase this rate to the block-letter reading rate.

F. Reading-Rate Determinations

During the sessions in which reading-rate determinations were made, a strict schedule of practice, rest, and test periods was followed. There were one-hour sessions and four 2-minute tests. During each test the equipment was set to present the words at a predetermined fixed

rate. The subject called out the words as she recognized them and was corrected only in the extreme cases in which a sentence or more was missed. Only correct word responses were counted in determining the reading rates.

The results of these determinations are shown in Fig. II-9. Some of the variability in these reading-rate determinations is due to variations in the difficulty of the reading material. The textual material used in each session is given in Table II-2. However, other factors also significantly influenced the reading rates. For example, the large dip in the curve in Subject 11's record was in part caused by giving him too high a presentation rate (31 wpm) too soon. His accuracy fell to such an extent that his correct wpm rate was lower than it had been for slower presentation rates. Also, the rapid rise in reading rates from about 20 wpm to 30 wpm for S3 was undoubtedly influenced by the large amount of practice at a 24-wpm presentation rate and by the programming change which increased the on-time of the letter patterns (see discussion in connection with Fig. 2-6 in Appendix D).

Besides textual material, random (equally probable) letter tests were also given to S3. The results of these tests are shown in Fig. II-10.

G. The Effect of Array Width*

An important question is how many stimulators are necessary for adequate perception of alphabetic shapes. The answer to this question is relevant to the extent of the spatial communication capacity of the tactile sense as well as the practical considerations in the design of devices. In an attempt to shed some light on this question, sessions 29 to 37 with S3 were devoted to practice and tests with various effective widths of the stimulator array. The number of columns activated was varied by a slight modification of the computer program so that any number of columns from 1 to 12 could be used.

* The work reported in this section was carried out and reported by B. Lane.

Subject 3's index finger made contact with only four columns of the array, therefore tests were only run for array widths of one, two, three, and four columns. Since the letters used in these sessions were five columns wide, some degree of temporal integration had to be performed by the subject with each of the array widths used, the one-column array requiring the most integration. Thus, all of the reading done during this series of sessions was analogous to a slit scan of embossed letters, the variable being the width of the slit.

The parameters held constant throughout the experiments were as follows:

- (1) Presentation rate was 24 wpm using the Times Square 1 single-jump mode.
- (2) All text was taken from "The Beatle Book."
- (3) The bimorphs were synchronously pulsed at 250 pps with a 50-percent duty cycle (2 msec).

A strict schedule of reading and rest periods was followed for each one-hour experimental session, as follows:

Practice	10 min.	Practice	10 min.	Practice	10 min.	Practice	10 min.
Rest	1 min.	Rest	1 min.	Rest	1 min.	Test	1 min.
Test No. 1	2 min.	Test No. 2	2 min.	Test No. 3	2 min.	Test No. 4	2 min.
Rest	2 min.	Rest	5 min.	Rest	5 min.		

Reading accuracy was tabulated for each of the four 2-minute tests, and an average for the session was calculated from these four results. In all cases the reading during each test was uninterrupted, with the subject's mistakes or omissions being verbally corrected, and accuracy was defined as the percentage correct of all words presented.

Figure II-11 is a graph of the results of this series of tests. The points on the graph are averages of all tests at each dial setting, and the highest and lowest test scores are also indicated.

H. Discussion

All three blind subjects were reading material aimed at their age and educational levels at a rate of over 20 correct wpm (24-wpm presentation rate) by the end of 17 hours of training. (Subject 13 attained

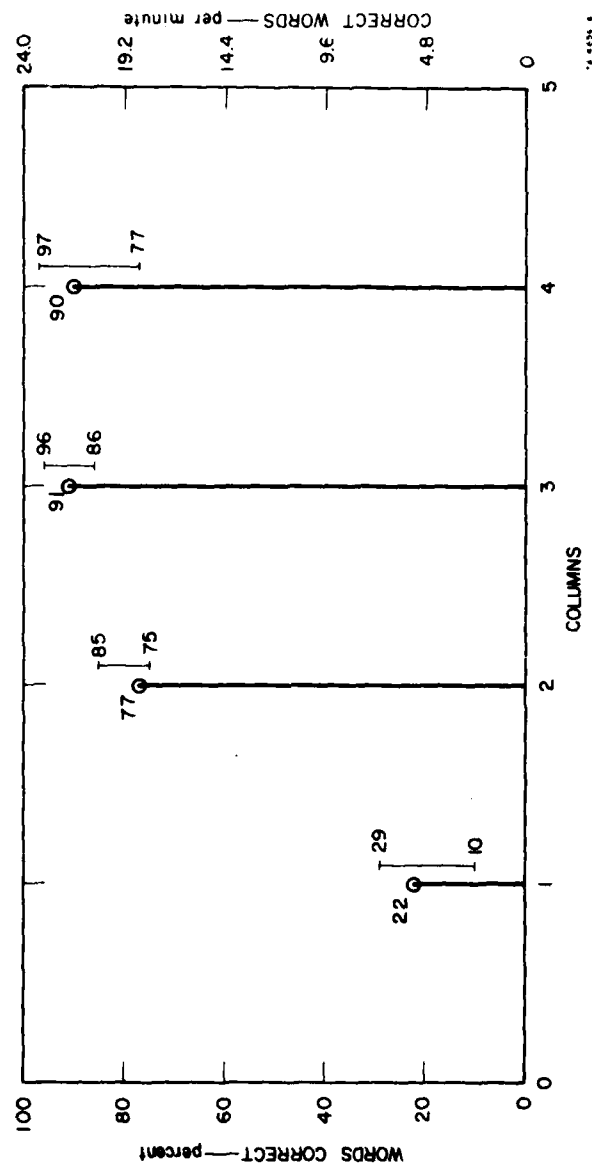


FIG. II-11 READING ACCURACY VS NUMBER OF COLUMNS
Points equal average of eight tests.

this rate after only six hours of training.) Even though the reading rate determinations with S3 were interrupted for other experiments, she reached a correct-word reading rate of above 30 wpm (37-wpm presentation rate) by her 45th session. By comparison, Geldard (1957) reports a reading rate of 35 wpm, after 16 hours of training with an arbitrary tactile code employing five stimulator locations, three intensities, and three durations. This rate was obtained with only one subject, however, and it is not clear whether 35 wpm was the presentation rate or the correct-response rate. Also, the difficulty of the material read, which we have found can affect the reading rate by more than 2 to 1, is not discussed.

When one considers how long it normally takes to become proficient with analogous tasks, all of these times are so short that they can only indicate the potential, not suggest any sort of limits.

The fact that the material was presented at a constant rate in our sessions undoubtedly had a great effect on the reading rate. As with visual reading, a much better system would be to allow the subject to control the presentation rate. An important problem to be studied is what form this control should take, as well as other capabilities for "browsing" through the material.

Even though our training sessions were somewhat informal and not strictly controlled, we have the impression that there is a temporary plateau in reading rate around 20 wpm and that it takes considerable time to take the next jump to around 30 wpm. It is interesting to speculate that these plateaus correspond to letter-at-a-time recognition and the beginnings of word-at-a-time recognition, respectively. We will have a better understanding of these plateaus and subsequent learning performance as these training sessions continue.

In the experiments on array width, the experimenter could not read the visual display as well as S3 could read the tactile display with one- and two-column widths. While this is an informal observation, it suggests that a subject may achieve better temporal integration with touch than with vision. Visually, the difference between one- and two-column array widths seemed to rest on the ability to perceive corners

in the two-column width, which is difficult if not impossible with the one-column width.

The research on the optophone, reviewed by Freiburger and Murphy (1961), permits a comparison with an analogous one-column auditory display. They report a 10-wpm reading rate after over 100 hours of training. The large improvement we found in going from one to two columns may account for part of this relatively poor performance. However, the experiments with the optophone involved manual tracking of the material by the subject, which was probably also a factor.

There are several practical situations in which tactile reading of alphabetic shapes has advantages over an arbitrary code. The practicality of a direct optical-to-tactile transducer that would give the blind direct access to the printed page depends on alphabetic shapes being tactually readable. Moreover, alphabetic shapes are spatially redundant stimuli and less susceptible to noise than a nonredundant code, an important point in any communication situation.

The importance of character shape is indicated by the sessions in which the typewriter font was used. The serifs make these letters less distinguishable tactually, but it is already clear that they can be learned with the present equipment in less than 10 hours.

III SPECIALLY DESIGNED ALPHABET*

Initially, subjects have considerable difficulty reading the capital-letter alphabet used for the blind subjects. The general reaction was that there was just too much air; i.e., each letter felt like a blast of air without much structure. The primary purpose of the study discussed in this section was to determine whether an easily learnable special tactual alphabet could be developed for use in conjunction with the 12-by-8 airjet array. The results showed that such an alphabet could be developed. In the initial study, two project personnel were used as subjects. The approach was to use one of the subjects, S1, to develop an alphabet of 26 distinguishable symbols and then to use the second subject, S2, to get a measure of learning rates with the final alphabet form. The results of this study are discussed below. Subsequently, other tactually-naive subjects were taught the alphabet; the results of those training sessions are discussed separately.

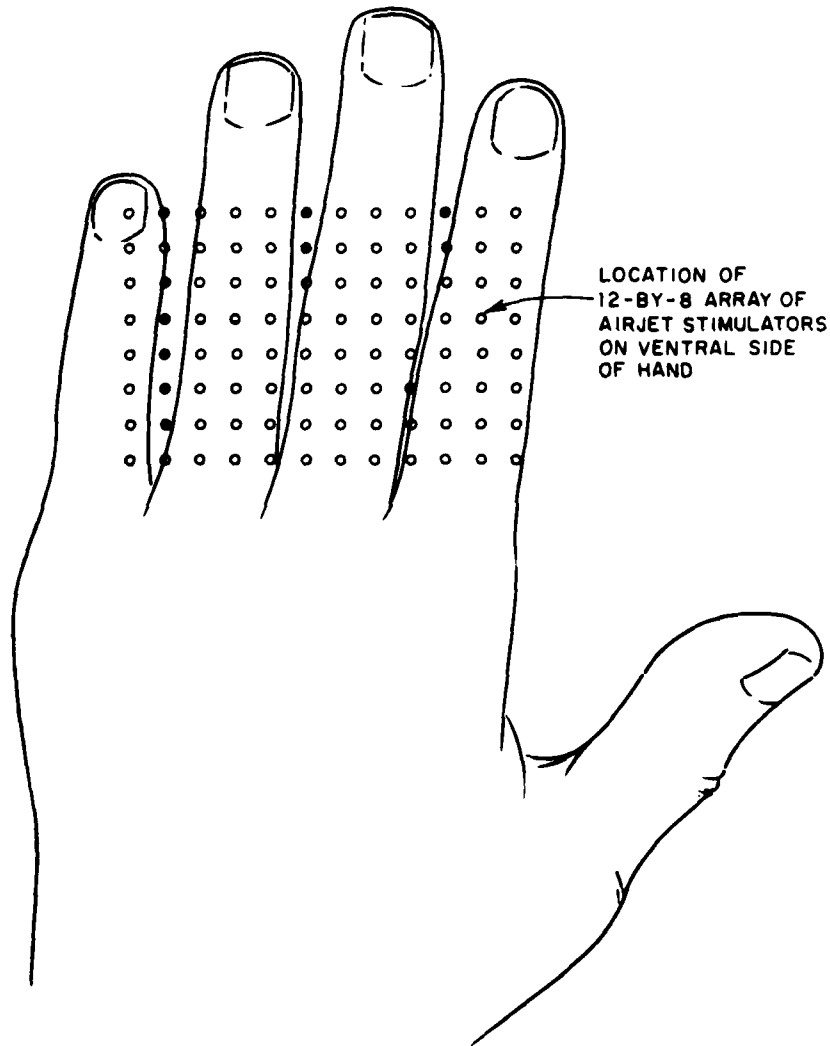
A. Developing an Alphabet

The procedure for designing the alphabet was subjective and based on trial and error methods. In order to take advantage of possible positive effects from the transfer of visual imagery to tactual imagery, the standard alphabet was first presented in block letters. A progressive process of modifying the letters was then pursued, while at the same time, the attempt was made to maintain elements of similarity to the standard letters. In many cases this was possible, but in others, unrelated symbols were substituted to facilitate rapid discrimination. Letter modifications continued until each letter could be recognized with almost perfect accuracy when the letters were presented in random order in the frame presentation mode, with about 150 msec duration, and

* This section differs from the previous one in that random letters were presented in this study, in contrast to textual material. Thus, since the sequential redundancy of English was not present, each stimulus contained correspondingly more information. This fact should be remembered when comparing the data in the two sections.

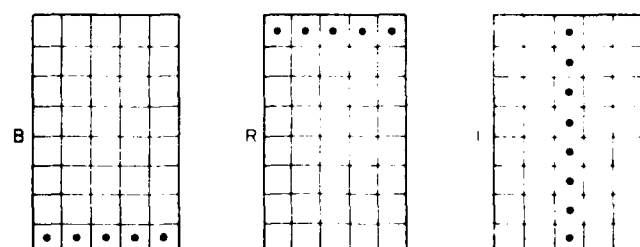
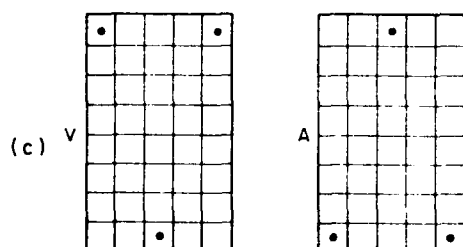
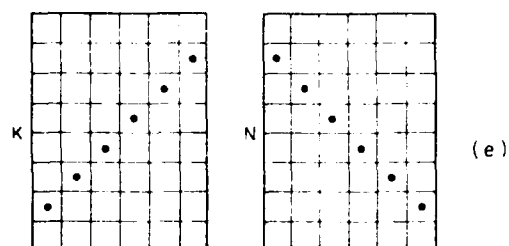
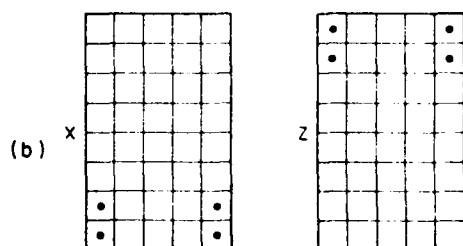
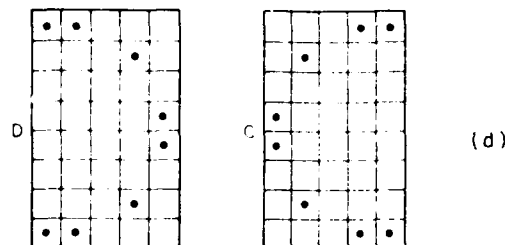
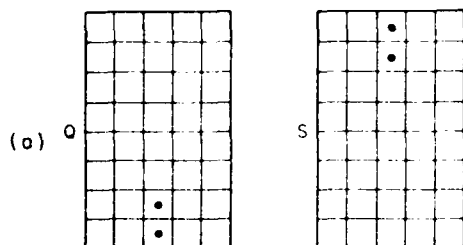
with interletter spacing, of approximately 1 second. The stimulation site was the ventral surface of the fingers on the left hand, as indicated in Fig. III-1.

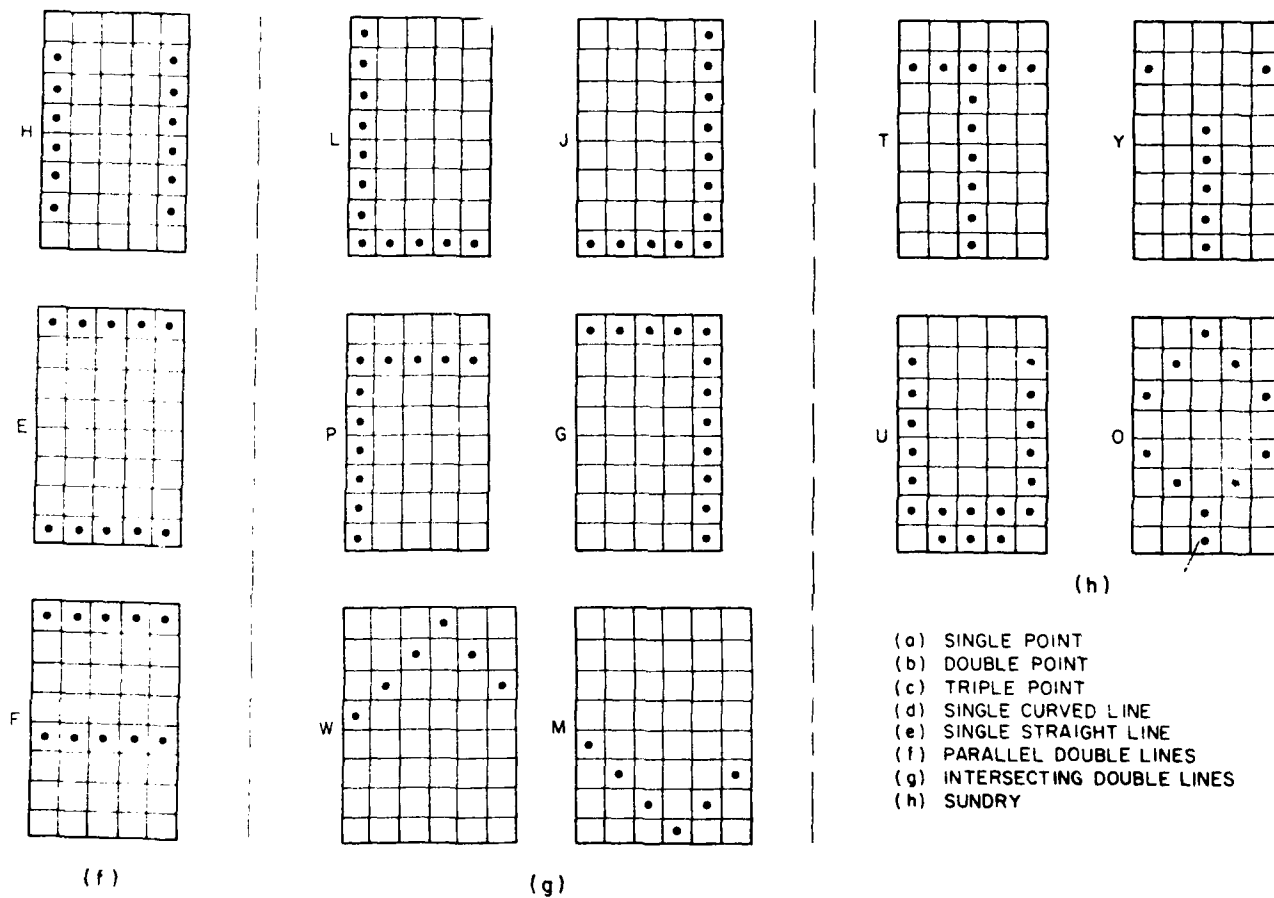
The alphabet derived in this subjective manner, using the frame presentation, is shown in Fig. III-2. Its development required approximately 15 hours of computer time spaced in two-hour periods twice per week. The patterns of Fig. III-2 are assembled in groups rather than



RA-4719-25

FIG. III-1 POSITION OF AIRJET ARRAY FOR STUDIES OF TACTILE READING





RD-4719-45

FIG. III-2 EXPERIMENTALLY DEVELOPED ALPHABET

2

alphabetical order. The various groups are (a) single point, (b) double point, (c) triple point, (d) single curved line, (e) single straight line, (f) parallel double lines, (g) intersecting double lines, and (h) some sundry patterns.

1. Comments on the Alphabet Set

The three "sundry" patterns of the last group remained from early tries in which common block letter forms were used. By altering and abstracting enough of the other letters, these three patterns remained fairly distinguishable.

For each of the individual points of the single and double-point patterns, two stimulators instead of one were used as shown in Fig. III-2. The triple-point patterns could probably also be doubled to some advantage, although they are readable as is. Vertical doublets could also be used. One quadruplet dot pattern was tried, with four dots arranged in the four corners, but this pattern was difficult to distinguish from a crossed-line "X" pattern.

The two curved-line patterns are readily distinguishable. Vertical curves (i.e., curves opening to the top and bottom) would not be distinguishable from the W and M patterns, which are straight-line versions of these vertical curves.

The straight-line patterns are quite distinguishable. It appears that 45 degrees is about the minimum angular difference for lines to be easily distinguished. As it is, confusion can sometimes arise between the N and I and the K and I if the hand becomes a bit skewed on the array.

The disconnected double lines are very distinguishable. Note that the separation between the two horizontal lines of the F is the same as the separation between the vertical lines of the H.

The corner patterns of the L, J, P, and G are easily distinguished. By rotating these corner patterns 45 degrees we can get four other patterns, two of which are used as the M and W. The other two possibilities are patterns with the apexes pointing left and right like the sloping lines of the ordinary letter K and its mirror inverse but these would probably be confused with the circular patterns of the C and D.

The T is fairly good but probably could be strengthened like the U by doubling the top bar. Without the double bar for the bottom of the U, the pattern was sometimes confused with an H. Distinguishing between the T and Y would probably be easier if the dots of the Y were doubled.

2. Modifications from Second-Subject Training

After S1 had successfully acquired a meaningful alphabet for himself, S2 began learning the same code. He was well acquainted with the alphabet visually before attempting to learn it tactually.

The initial stimulation site on S2 was the palm of the left hand; however, it was found that the palm was somewhat less sensitive than the fingers, and hence some difficulty was encountered with some letters, particularly the W, M, and X. The W and M were hard to distinguish from the R and B, respectively. The two dots of the X were often sensed as a single line, which is the B. It is interesting to note that the subjects had little trouble distinguishing between the Z and R, which both appeared on the distal part of the palm. This part of the palm is more sensitive than the heel of the palm, where the X and B appeared.

Observations made by S1 suggested that movement of the hand during stimulation was helpful; therefore, the procedure was modified so that stimuli were presented by the "Times Square" moving-letter display. This procedure sharply reduced errors by S2 and a rerun for S1 also produced a significant improvement in performance. In this mode, both subjects were capable of errorless discrimination of randomly ordered letters at a rate of almost one per second.

Observations by S2 initiated the following investigations in the attempt to determine the ideal method of stimulus presentation.

a. Edge Effects

It was found that considerable information is obtained from sensations at the edges of the display. Assume, for example, that the letter L moves across the display. All at once a strong line is felt on the fingers at the right (entry) edge. This sensation at once delineates the number of letter possibilities. Then at the left (exit)

edge, the strong line disappears, but continued excitation occurs at a single lower point. Only when the pattern strikes or leaves the fingers are these effects felt, but often this information is enough to identify the letter. The effects are essentially the same whether the fingers are held loosely or closely together, and whether three, two, or even one finger is used instead of four. Sometimes a clear sensation of the letter pattern is perceived as the pattern moves across the fingers, and in this case edge information is unnecessary; but sometimes a clear sensation is not achieved, and then edge information is very useful.

Significant edge information is obtained from almost every letter. For example, with K or N, a strong sensation of a point moving vertically along the edge is felt as the letter enters and leaves the display area. Or, with the W and M, there is a sequential up-and-down sensation.

b. Letter Packing

With a letter appearing every seven columns, portions of three letters can simultaneously appear on the display. When the spacebar is energized between each letter entry, then every other letter position is empty. With this spacing, one letter leaves the display as another enters. With a double spacebar between letters, only a single letter at a time passes the display.

Both subjects noted little effect when the packing was changed from two spacebars to a single spacebar. However, when the letters were packed with no spacebars between, it became almost impossible to distinguish the rather complex composite patterns moving across the display. But when the basic letter packing was increased so that there was a letter every eight columns, with no spacebar between letters, both subjects found that separate letters were again readily distinguishable. It was decided, therefore, that considerably more training may be required as letters become more closely packed. A second observation is that because some of the letter patterns have disconnected portions, there is a possibility that a portion of one letter will be perceived as part of the adjacent letter; for example, a sequence ZIZ might be

sensed as SYS, or vice versa. However, again, this situation might be improved with extensive training and letter redesign. Language context, of course, also helps.

c. Rate of Presentation

With a letter every eight columns, S2 was able to read a random list of letters at a rate of almost one a second. (Individual frame time was about 125 msec; it takes eight frames for a letter to move past any given point of the array.) At this rate, some errors were made, probably because training had not advanced to the point where letter response was automatic and there was still significant delay between the pattern perception and the letter calling. An interesting effect noticed by both subjects is that when letters were packed closely together in a sequence, once attention was distracted from the sequence it was difficult to start again. While identification is going well, there is a strong sensation of familiar patterns moving across the fingers, and they can be consciously followed. One can focus attention on different portions of the letter patterns as they move across the display. When attention is lost, however, the subsequent excitation does not seem to be moving but merely feels like a complex pattern playing on the hands. Generally it is the passage of a particularly simple configuration, say a double-bar H or single-line I, that "resets" the subject, and all at once familiar patterns are again moving across the display.

d. Number of Fingers Used

The two subjects tended to have similar reactions to the various phenomena discussed thus far. However, significant difference was noted in the effects of different numbers of fingers used with packed letter sequences. Subject 2 could not read tightly packed letter sequences when using all four fingers. He could not isolate various portions of the complex moving display for individual letter identification. However, when using only two fingers and only six of the twelve display columns, he could do very well. In fact, the letter-a-second rate noted above was achieved under these conditions. He could perform nearly as well reading with only a single finger. But with three and

four fingers, the steady sequence of patterns were essentially unreadable. Subject 1, however, appeared to have little problem using four fingers. He felt that the results with four fingers and with two fingers were approximately equal, with a slight preference, in fact, for four fingers.

Although S2 could read fairly well with a single finger resting on the array, results deteriorated if the finger received information from fewer than three columns. With the airjets spaced on 1/4-inch centers, a single finger can receive excitation from about five columns of the display. If as many as nine columns are covered so that the finger receives excitation from only three adjacent columns, reading is still quite good. However, if 10 columns are covered so that excitation is from only two adjacent rows, reading deteriorates considerably; and with only one column of stimulation, the results are poor. In other words, it seems, at least for S2, that there is some optimal mix of spatial-temporal excitation. With more than two fingers and six columns of the display, and with less than three columns and one finger, results deteriorate. These subjective results agree, at least as far as minimum width is concerned, with the quantitative study reported earlier in Section II.

B. Training Tactually Naive Subjects

Although two experimenters had learned this alphabet, it was felt that the validity of their accomplishments should be checked against the performance of tactually naive subjects. For this purpose, four male high-school students, ages 16 to 19, were hired for about two months to learn to read the symbolic letters when the letters were presented randomly. Other objectives were to measure, under standardized conditions, the degree to which each letter was confused with all others and to attempt to establish tentative limits on the speed with which separate signals could be recognized with accuracy.

For this study the alphabet of Fig. III-2 was modified to that shown in Fig. III-3. The main changes were:

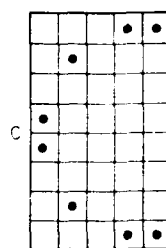
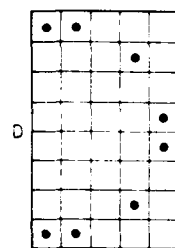
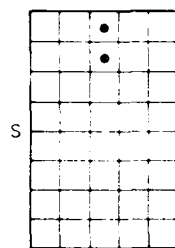
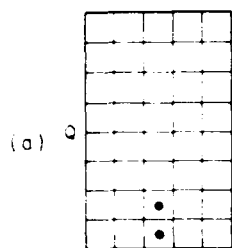
- (1) All letters were standardized to five-column width.
- (2) The points of the A and V were strengthened.
- (3) The vertical bars of the H were brought closer together. This not only improved recognition of the H but considerably reduced interletter interaction, e.g., reading the sequence HI as IH.
- (4) The T and P were raised to standardize the heights.
- (5) The tail of the O was dropped.

The four subjects were initially presented with a set of flash cards and were asked to memorize the alphabet visually to a criterion of three errorless presentations of the entire alphabet. Each subject was tested at the beginning of the next session and each was successful in recognizing all letters.

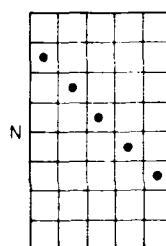
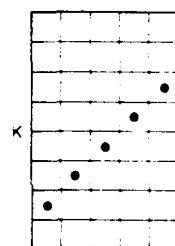
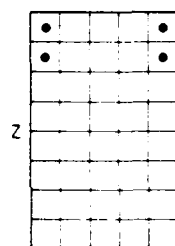
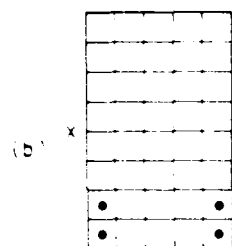
To minimize computer time, two subjects were trained simultaneously in the early sessions. To make this possible, the 8-by-12 airjet array was split in half so that each subject used only an 8-by-6 array, and the computer program was arranged so that the identical information was presented on each half array. The subjects were seated opposite each other with a screen placed between them to prevent visual contact. All subjects used the index and middle fingers of the left hand as receptors of the stimuli. These fingers were extended from an arm-and-hand rest over and approximately 1/4 inch above the array.

The airjet stimulus was presented in all cases by the Times Square Program, in which the moving symbol passed across the two fingers at a previously fixed velocity and spacing between letters.

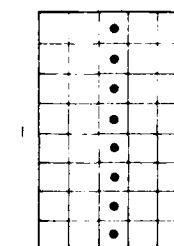
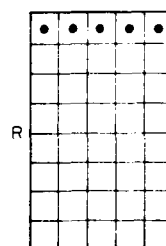
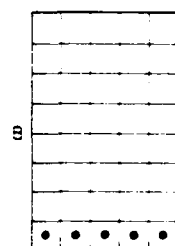
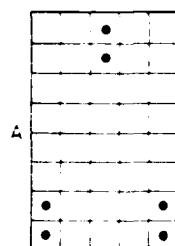
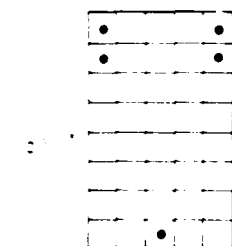
During the initial session, each subject was allowed to see a visual display of each letter while experiencing the tactile stimulus. Following this, the subjects were required to write down their responses prior to receiving auditory feedback. In these initial trials the presentation speed was arranged so that each letter required 0.525 seconds to pass across the six columns of the half-array, with a spacing between letters of (0.525×6) or 3.15 seconds; that is, there were five blank letter spaces between each actual letter. Air pressure was adjusted at 10 psi. The sequence of letters was controlled from a previously

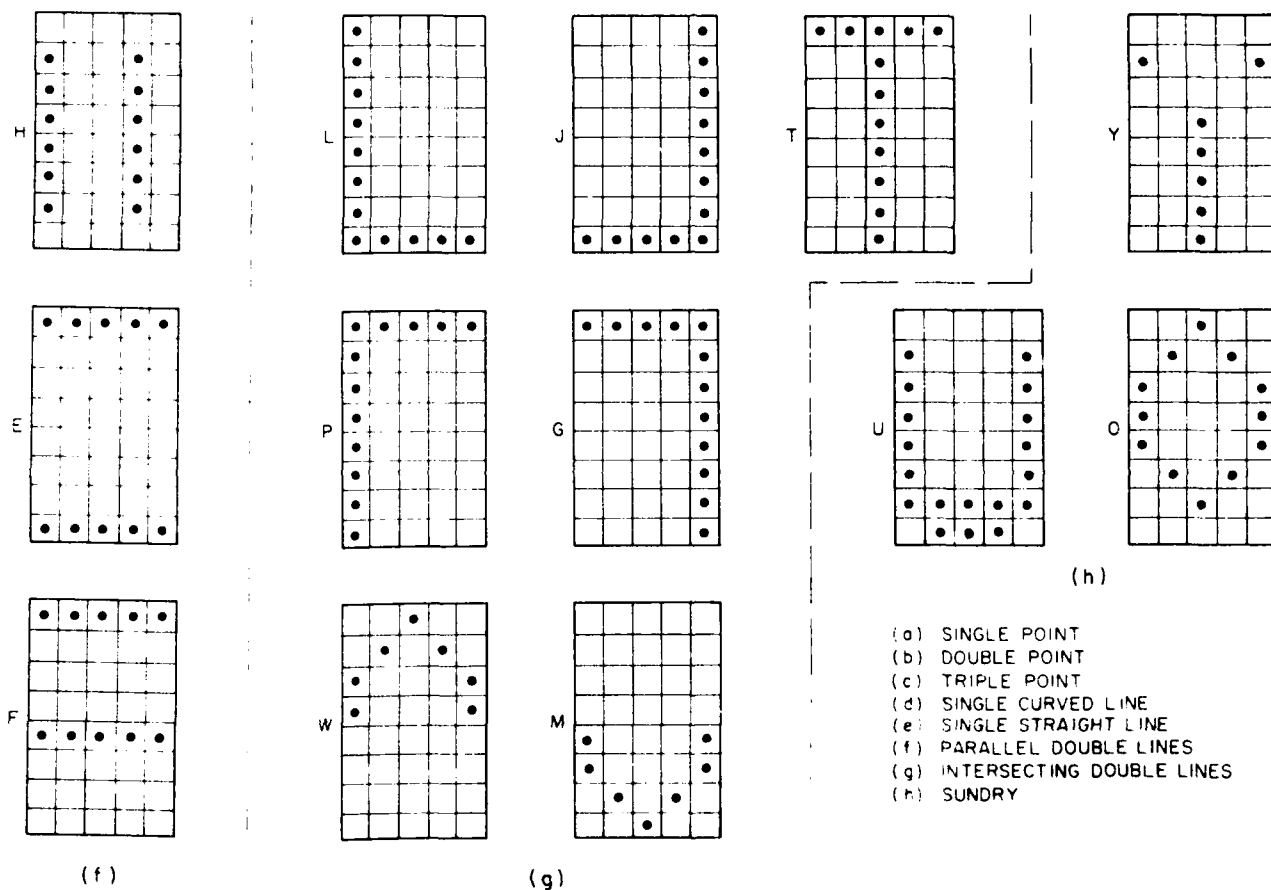


(d)



(e)





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FIG. III-3 MODIFIED VERSION OF
EXPERIMENTALLY DEVELOPED
ALPHABET

arranged list of $6 \times 26 = 156$ randomized letters. In each experiment a different starting point in the list was selected.

By the third session the subjects found it confusing if auditory feedback was given between letter presentations, and they reported that they tended to write down their response hurriedly in anticipation of the feedback.

During the first six sessions, the letter spacing was held fixed at five blank spaces between each letter presented, but the speed of the moving display was continually increased. By the sixth session, the velocity was such that it took 0.38 seconds for a letter to pass any point of the array. At this velocity, and with five blanks between letters, the actual presented letter rate was (6×0.38) , or slightly more than two seconds per letter.

Initially, each pair of subjects was trained identically at a rate determined by the slower member of the pair, but the two pairs were allowed to progress independently. Actually, one pair of subjects progressed much slower. In fact, one member of the poorer pair was retired after 15 sessions. Despite his having received special attention, this subject did not, even at slow rates, achieve sufficient proficiency. The second member of that pair performed satisfactorily, though with less skill than either member of the second pair. However, experiments with this subject terminated after about 20 sessions because the subject could no longer participate. One of the subjects of the better pair had to drop out for several weeks after the twentieth session; therefore, there is continuous data on only one subject, S4, who, incidentally, was the best of the four. His accuracy curves for each session are indicated in Fig. III-4. On the same figure is plotted the number of correct letters per second. In interpreting the latter curve, the following changes in letter spacing at Sessions 7, 9, 13, 17, and 21 must be noted. From the seventh through the 24th session, the velocity of the display was maintained constant but the number of blank spaces was progressively reduced as follows: Only four blank letter spaces on the seventh session; three spaces on the ninth session (at this rate the subjects did not have time to write their responses, and a tape recorder

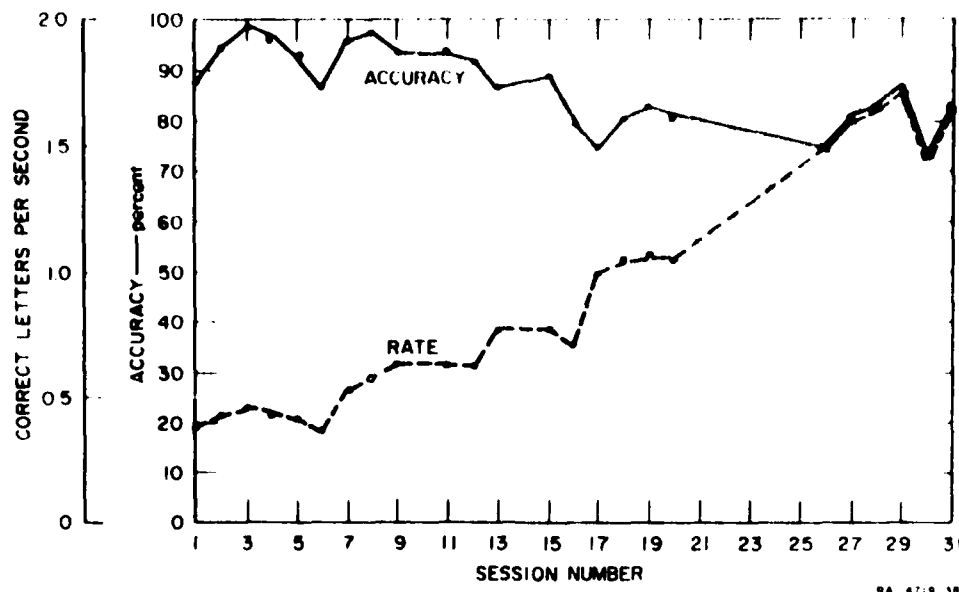


FIG. III-4 ACCURACY (PERCENTAGE OF CORRECT RESPONSES) AND RATE (CORRECT LETTERS PER SECOND) BY SESSION FOR S4

was used; this procedure was maintained in all further sessions); two spaces on the thirteenth session; one space on the seventeenth session; and no spaces on the twenty-first session. With no empty letter positions, i.e., with the letters closely packed, the overall letter rate was approximately 0.43 seconds per letter.

With closely packed letters it was found that the subjects would often tend to lose their place and become confused, allowing a long series of letters to pass without responding. A subject would become "reset" with the passage of a particularly simple pattern, like the letter I, and would then respond with characteristic accuracy until he became confused again. (This same phenomena was noted in the initial sessions, when project personnel were used as subjects.) In view of this erratic response the mere statement of a total average accuracy figure is misleading. Therefore, in the data of Fig. III-4, accuracy is measured as a percentage of correct responses of the total actual responses. The problem of erratic response was diminished by allowing the subject to stop and start the display manually whenever he loses context.

To illustrate the types of errors made, a confusion matrix for Sessions 18 through 20 is shown in Fig. III-5 for subject S4. Note in particular the lack of symmetry in this plot, indicating that no particular pairs of letters were reciprocally confused. For example, a T was sometimes called a Y but never vice versa. The same result was generally true for the other subjects, indicating that the letter designs for this alphabet present no serious confusion factor. Looking over the entire data on all subjects, the following observations on letter confusion can be made:

- (1) No pair of letters was reciprocally confused by more than one subject.
- (2) Only two subjects had a reciprocal error. One subject confused YT and TY, while another had trouble with RSZ.

	RESPONSE																										TOTALS
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	
STIMULUS	A																										0
	B			1																							1
	C																										0
	D																			1							2
	E				1		1	1																			3
	F																										0
	G					1				1												1					3
	H																										0
	I										1																1
	J											3															3
	K																										0
	L									1																	1
	M												1									1	4				6
	N																										0
	O																										0
	P									1																	1
	Q																				2						2
	R																	1	1								3
	S																			3							6
	T									1								3	1						3		8
	U																										0
	V																								1		2
	W																										1
	X																										1
	Y																										0
	Z										1									2			1				6
TOTALS	1	5	0	1	2	2	4	0	1	2	1	4	0	2	0	4	1	7	2	1	1	1	4	0	4	0	6

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FIG. III-5 CONFUSION MATRIX FOR SESSIONS 18 THROUGH 20, SUBJECT S4

- (3) All subjects experienced some confusion with X.
- (4) M, Z, Y, T, and P were confused to some degree by all three subjects.

C. Discussion

It was encouraging that with so little effort it was possible to devise a special alphabet which a subject who had as little as 39 sessions, or about 15 hours of training, could perceive at a rate of almost two random letters per second with about 80-percent accuracy. It seemed clear that with further modification of the alphabet set, and with considerably more training, significant improvement in performance could be obtained. However, at the time these results were obtained it was felt that rather than continue with extensive training on this special alphabet, we might more profitably engage in some basic experiments with this alphabet, while extensive training sessions were being continued with the blind subjects and the block-letter alphabet. Hence, further work with the special alphabet was in connection with the study reported in Section VI on the effects of pattern movement. We hope to renew alphabet-design studies with improved display techniques and also to consider different forms of codes.

IV TACTILE TRACKING EXPERIMENTS

A. Introduction

Two-dimensional visual and tactile tracking experiments have been performed using compensatory-type displays. Three kinds of compensatory displays were used, an oscilloscope, a 7-by-7 array of neon lights, and a 7-by-7 array of airjets. For the lights and airjets, the x and y error signals were sampled every 150 msec and each was quantized into seven equally spaced levels. The corresponding row and column of both 7-by-7 display arrays were activated so that only the stimulator at the intersection was energized. (The equipment is described in Appendices A and F.)

A photograph of a subject engaged in a tracking experiment is shown in Fig. IV-1. While this photograph shows the tactile stimulator array on the forehead, all experiments reported here were performed with the region of stimulation arbitrarily chosen in the vicinity of the nose, with the reference stimulator indicated by actual contact between the center airjet nozzle (which was extended) and the tip of the nose.

The experiments with the oscilloscope display were performed to give a basis for comparison of our results with the results reported in the literature. Experiments were performed with the array of lights to determine how much the visual performance is degraded by the sampling and 7-by-7 quantization. The results with the quantized tactile display can therefore be compared with an analogously quantized visual display and a continuous visual display.

In all three displays, the task was to keep the error stimulus in the center, the position of the error stimulus away from center indicating the direction and magnitude of the error. All three displays were constructed so that when the error was larger than the full-scale range of the display, the stimulus remained at the edge of the display (thereby indicating the direction of the error) instead of disappearing off the scale.



FIG. IV-1 EXPERIMENTAL ARRANGEMENT FOR TWO-DIMENSIONAL
TACTILE TRACKING

B. Effect of Display Gain with Low Command Frequencies

In initial experiments, command signals composed of the sum of three sinusoids of frequencies 0.05, 0.1, and 0.2 cps, all of equal amplitude and arbitrary phase, were used. An analog computer generated these command signals, computed the error, and computed the integral of the squared error. Figure IV-2 shows the computer program.

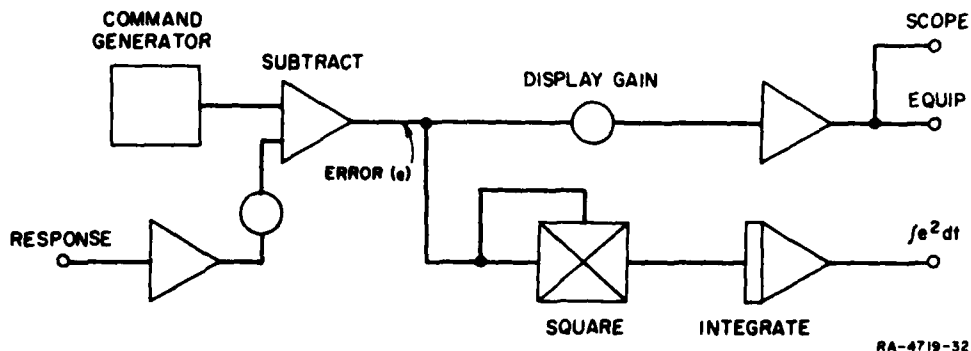


FIG. IV-2 ANALOG COMPUTER PROGRAM FOR EACH COORDINATE
IN THE INITIAL COMPENSATORY TRACKING EXPERIMENTS

One subject was used for all three displays. After several hours of practice, data were taken for all three displays and for various values of gain for the displayed error. The results averaged over seven sessions, each of several hours duration, are shown in Fig. IV-3. The ordinate is the integral of the squared error over 60 seconds expressed as a percentage of the integral of the squared command over the same 60 seconds. On this basis, if the subject does not move the joystick, the percentage mean-squared error is 100 percent, and if the subject tracks perfectly, the percentage mean-squared error is zero. Both x and y mean-squared errors were averaged together. The abscissa is display gain expressed as the ratio of peak command to the signal for full scale on the displays, for neutral stick. That is, if the gain is unity, the maximum command signal with no movement of the joystick results in a displacement of the error marker on the display equal to full scale.

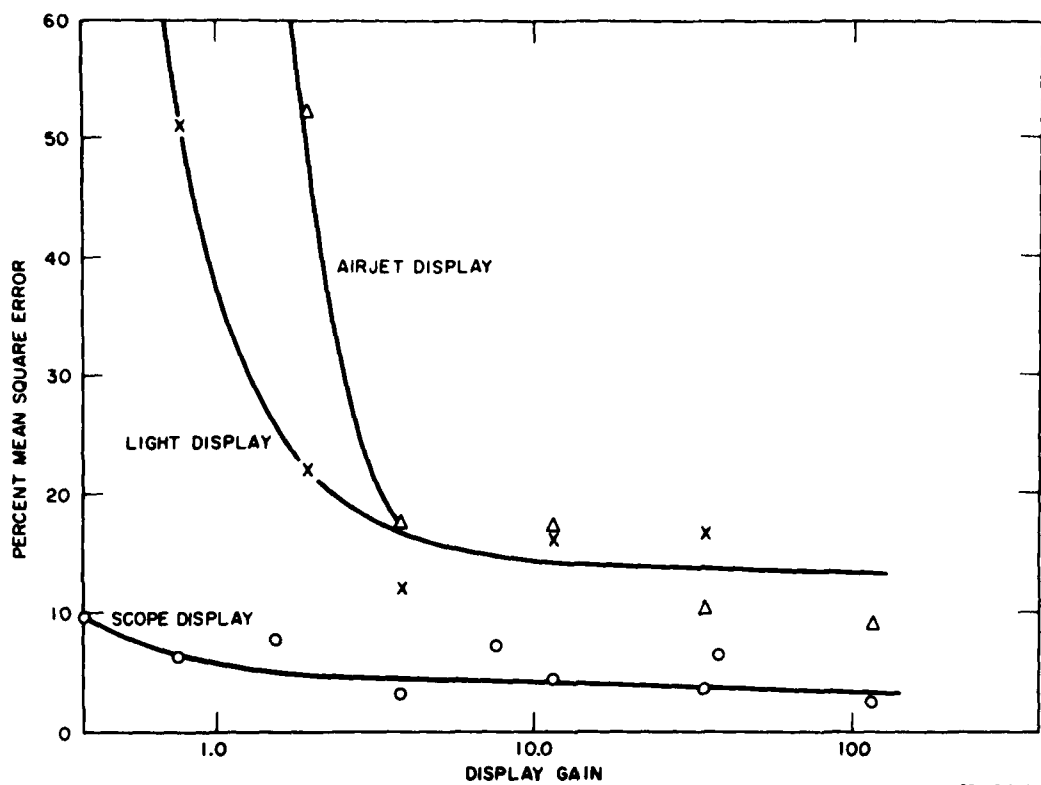


FIG. IV-3 PERFORMANCE VS DISPLAY GAIN FOR COMMANDS COMPOSED OF 0.05, 0.01, AND 0.2 CPS

In Fig. IV-3, the difference between the scope and light display curves represents the reduction in performance resulting from quantization of the error voltages. One way of looking at the performance with the 7-by-7 display arrays is to relate the mean-squared error to some equivalent constant error, \bar{n} , expressed as an equivalent number of lights or airjets on the array. This relation is

$$(\bar{n})^2 = 0.26 \overline{e^2} k^2 ,$$

where the constant of 0.26 results from the particular gain and quantization levels used in the system, and where

$\bar{e^2}$ = the integral of the squared error divided by the integration time in seconds

k = the display gain.

Viewed in this way, at a gain of 4 in Fig. IV-3, the performance with the light display is equivalent to a constant error of 1.2 lights. At a gain of 100, the performance is equivalent to a constant error of 27 lights. In the latter case, since full scale from center along either the x or y axis is only three lights, the performance with a gain of 100 indicates that the error light stimulus was off scale most of the time. The relatively good performance at this gain suggests that direction information is relatively more important than magnitude information. However, it should be pointed out that typically the mean-squared error is not accumulated at a constant rate, but in jumps corresponding to large values of command signals, as shown in Fig. IV-4.

The relatively poor performance at low gains indicates that for the particular spacing of airjets used (1/4 in. apart) at this location (in the region of the nose), the sensory resolution was probably worse than with analogous light display. However, the close-to-identical performance with the airjet and light displays at greater gain settings indicates no significant difference in performance due to the tactile sense, at least at these command frequencies.

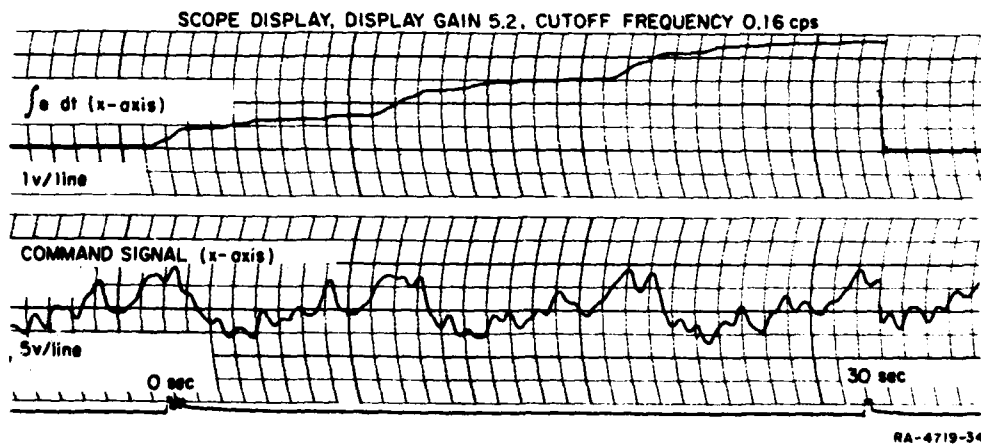


FIG. IV-4 TYPICAL COMMAND AND INTEGRAL SQUARED ERROR SIGNALS

C. Experiments Including Higher-Frequency Command Signals

At this point the experimental setup was revised so that more complex command signals could be used and more computations could be performed on the data. The resulting system is shown in Fig. IV-5. In this system the command signals, each consisting of the sum of 16 equal-amplitude sinusoids at frequencies of 0.1 to 1.6 cps, in steps of 0.1 cps, were prerecorded on magnetic tape. These command signals were then filtered, in real time, with a simple lag of adjustable corner frequency.

The results averaged over three subjects are shown in Fig. IV-6. In this figure, percent mean-squared error is plotted versus display gain for three values of the corner frequency of the command signal filter. The data for a display gain of 25 is replotted in Fig. IV-7 versus the bandwidth of the filter for the command signals.

Two major differences between these results and the results with lower-frequency command signals in the initial experiments are

- (1) Performance with the airjet display was significantly worse than with the light display; and
- (2) The percentage mean-squared error was higher for both displays, exceeding 100 percent in some cases.

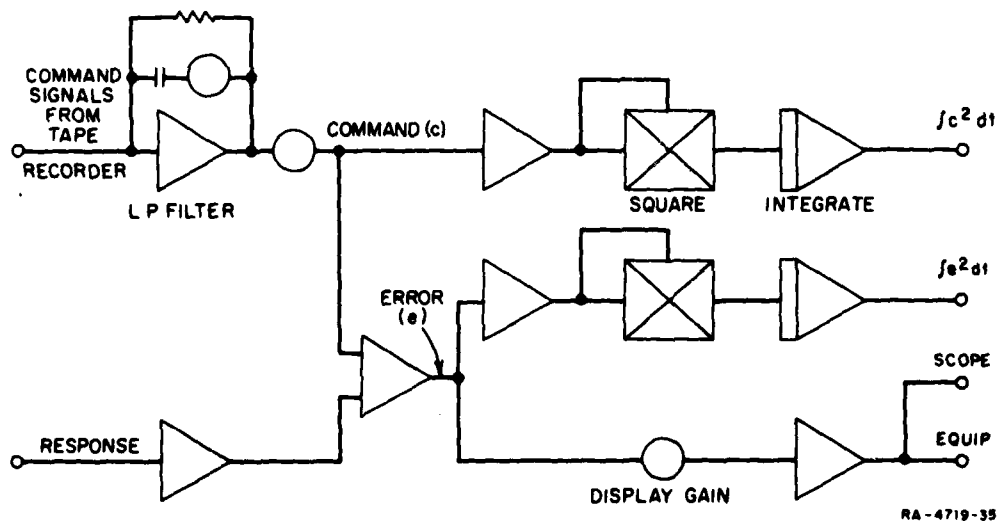


FIG. IV-5 ANALOG COMPUTER PROGRAM FOR COMPENSATORY TRACKING EXPERIMENTS USING PRERECORDED COMMAND SIGNALS

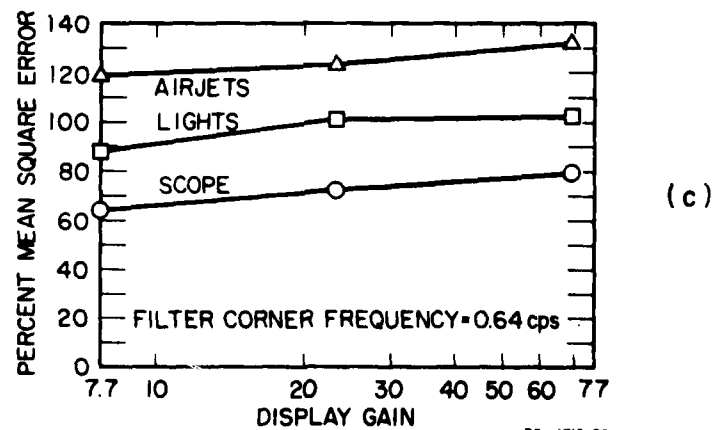
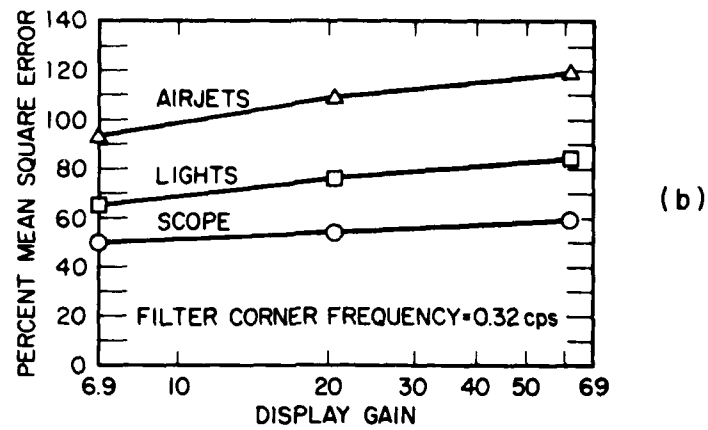
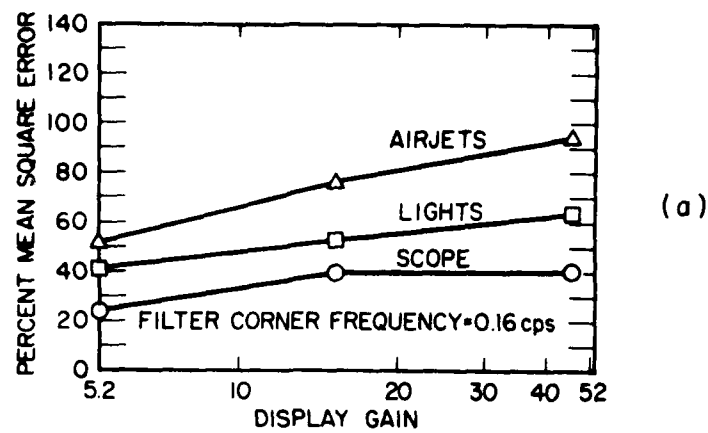


FIG. IV-6 PERFORMANCE VS DISPLAY GAIN
FOR THREE FILTER CORNER FREQUENCIES
(a) Filter corner frequency = 0.16 cps
(b) Filter corner frequency = 0.32 cps
(c) Filter corner frequency = 0.64 cps

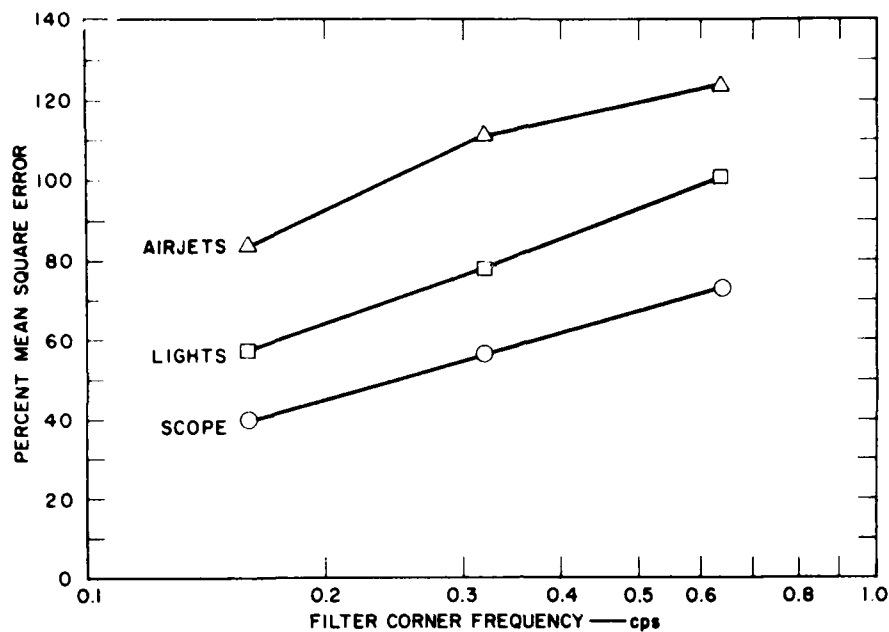


FIG. IV-7 PERFORMANCE VS FILTER CORNER FREQUENCY
FOR DISPLAY GAIN OF 25

The first difference indicates that either the frequency response of the tactile stimulators was poor enough to affect the performance or that the tactile reaction time was worse than the visual. In the experiments described later in this section no consistent difference was noted between tactile and visual reaction times. Thus, it appears that the former possibility was the case.

In order to see how a percentage mean-squared error of greater than 100 percent can reasonably occur, it is helpful to relate mean-squared error to the pertinent correlation functions. The required relation is

$$\overline{e^2}(\delta) = \varphi_{cc}(0) - 2\varphi_{rc}(\delta) + \varphi_{rr}(0)$$

where

$\overline{e^2}(\delta)$ = the mean-squared error between the command, delayed by an amount δ , and the response

$\varphi_{cc}(0)$ = the mean-squared command signal or the autocorrelation coefficient for the command

$\phi_{rc}(b)$ = the cross correlation between the command and the response evaluated at b

$\phi_{rr}(0)$ = the mean-squared response signal or the autocorrelation coefficient for the response.

Thus, if there is as much power in the response as in the command, the percentage mean-squared error would reach as much as 200 percent if the cross correlation between command and response went to zero. Typically, the response power is at least 70 percent of the power of these command signals.

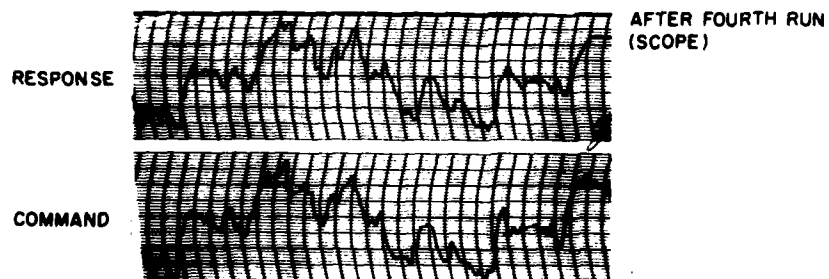
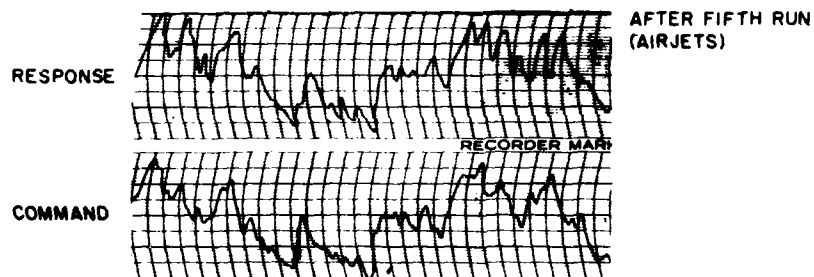
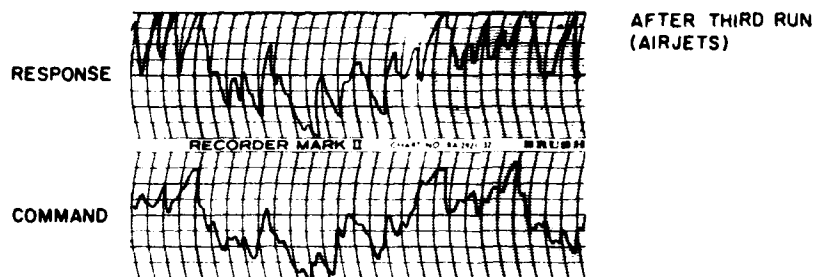
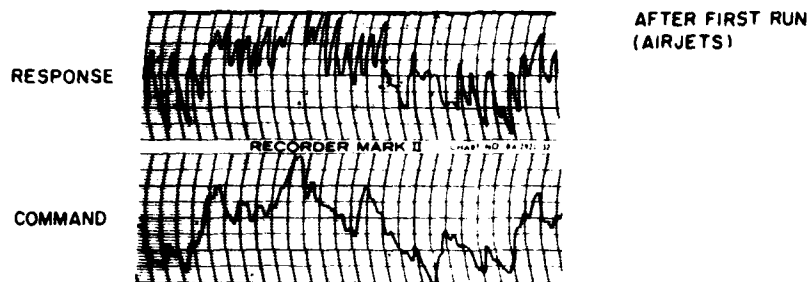
D. Improvement of Response by Training

As a result of the variation noted in the response which the subject gave for a fixed setting of gain and cutoff frequency, a brief investigation was made into the possibility of improving the response by training. As in the previous experiments, the prerecorded command consisted of the sum of 16 frequencies between 0.1 and 1.6 cps, in steps of 0.1 cps, filtered in real time with a simple lag of adjustable corner frequency. The command and the subject's response were recorded on a pen recorder; and since the training was done in a series of one-minute runs, the subject could be shown recordings of the previous run and understand the type of improvement required. A different part of the command tape was used for each run so that the subject could not learn the response to one section of command over the repeated trials.

The results of a typical training session are shown in Fig. IV-8 for the airjets at the lowest values of gain and cutoff frequency.

For comparison, the final result of a run with the scope is also given, showing that, at least at the gain and cutoff frequency used here, the airjet response could be made comparable to that of the scope, though the latter shows a delay of 0.2 to 0.4 second, whereas the airjets show a delay of 0.4 to 0.7 second.

In spite of the closer resemblance between command and response after training, the subject did not necessarily sense any improvement in his tracking performance. For example, the marked improvement shown in the response, suggesting that the response be "less jerky" or



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FIG. IV-8 EFFECT OF TRAINING ON PERFORMANCE
(chart speed 1 chart line/sec)

"of lower amplitude." The improvement was observed to level off after about five runs, after which the performance remained constant. It was also found that the training advantage was lost very quickly, and retraining became necessary after another four or five minutes of tracking.

E. Error Evaluation with Delay*

The human transfer function is often characterized as having a pure delay factor which arises from sensor excitation, nerve conduction, and computational lags. The following experiments were carried out to see whether introducing a delay between command and response before computation reduced the integral mean-squared error and if there was any significant difference between the continuous and discrete modes, as well as between the visual and tactile sense modalities in this respect. The displays used were, as before, an oscilloscope and two discrete displays consisting of the 7-by-7 neon light array and the 7-by-7 airjet matrix.

The experiments were initially performed as described above except that a Donner transportation delay generator (Model 3770) was used to delay the command signal just before computing the error, squaring, and integrating. Since an error signal is also used to drive the equipment, a second difference amplifier was required in the analog computer program to compute the error, using the undelayed command signal. The command, the sum of 16 frequencies previously recorded on tape, and the subject's response, were used to compute the error in real time for a number of runs, using different values of delay from undelayed command to 0.5 second.

The results obtained indicated that any effect attributable to the delay was lost in variation between runs, and it was therefore decided to record the response to a given command on magnetic tape and use the same run to compute the errors at different delays.

A new tape was prepared to provide the x- and y-axis command signals. The sum of eight frequencies of equal amplitude, 0.05, 0.2, 0.4, 0.65,

* This work is reported by H. Seeley.

0.9, 1.2, 1.5, and 2 cps, was generated by the analog computer and recorded with arbitrary phase relations on two of the four channels of the Ampex FM tape recorder. The x- and y-axis signals were recorded separately to prevent any correlation. These signals were then played back and filtered to provide the command, and the subject's response to these signals was recorded on the two remaining channels. Three values of gain and cutoff frequency were used, and for each type of display, three runs were recorded, making a total of 81 separate runs. One subject was used for the series, and the various combinations of gain and cutoff frequency were presented at random to minimize any long-term training effects.

A typical recording session ran as follows: For a particular setting of gain and cutoff, the subject was trained, as described earlier. When the performance showed no further improvement, three runs of 50 seconds each were recorded, each run being separated on the tape by 5 seconds of random noise. This whole procedure was then repeated for the other displays. The data were analyzed using the analog computer program shown in Fig. IV-9.

Each run was played back and the integral mean-squared error computed for settings of the delay between zero and 0.7 second in steps of 0.1 second. The delay quoted represents the theoretical delay between command and response; an extra 0.2-second delay was added to allow for

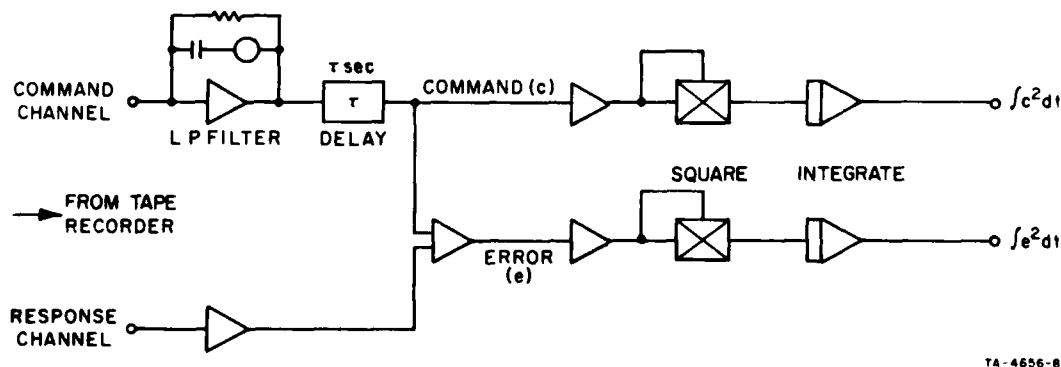


FIG. IV-9 ANALOG COMPUTER PROGRAM FOR EXPERIMENTS USING THE DELAY GENERATOR

the delay introduced by the separation between record and playback heads at the time of recording. The two channels of the delay generator, each set at half the required delay, were connected in series to minimize distortion, which was found to increase with the delay introduced.

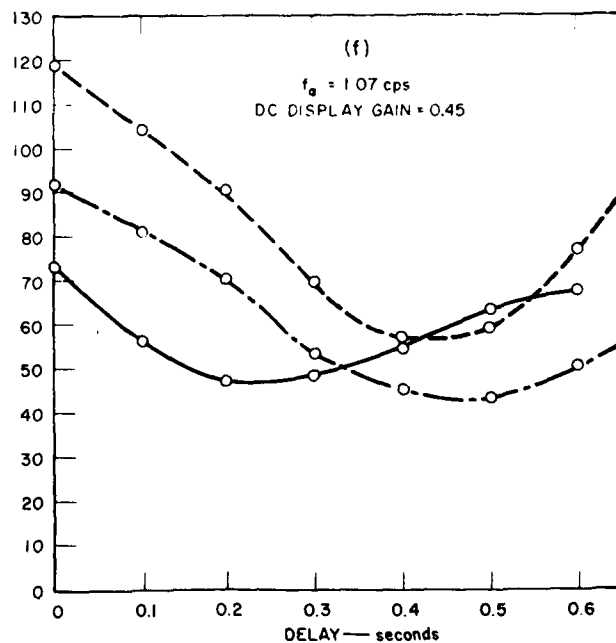
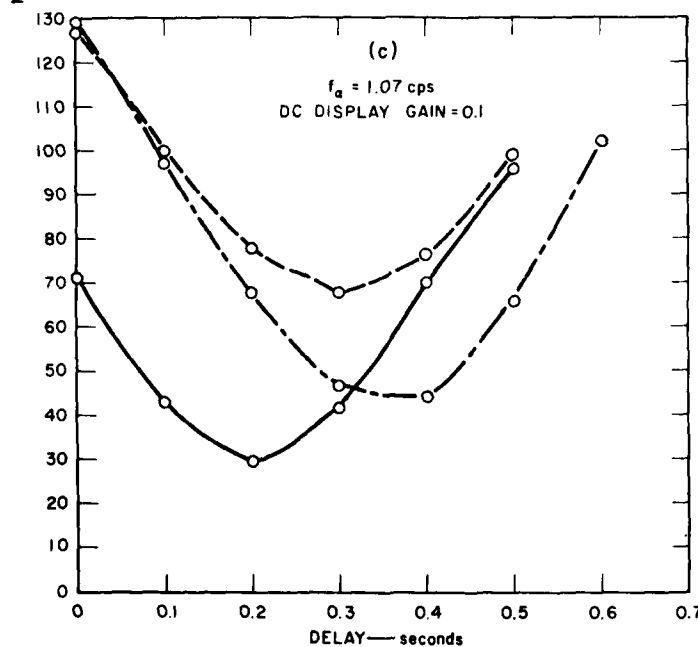
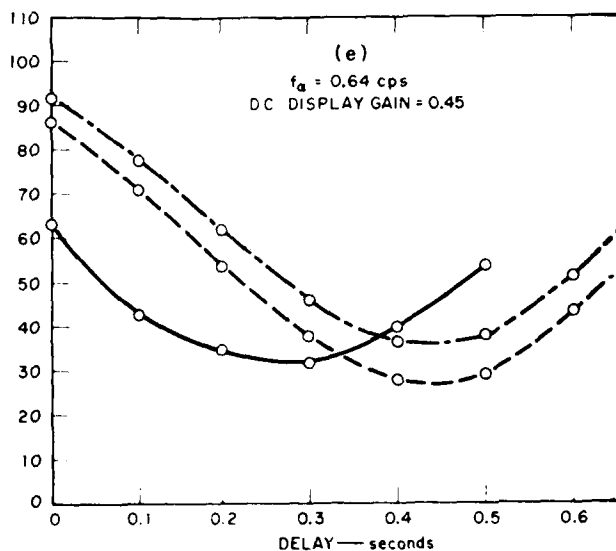
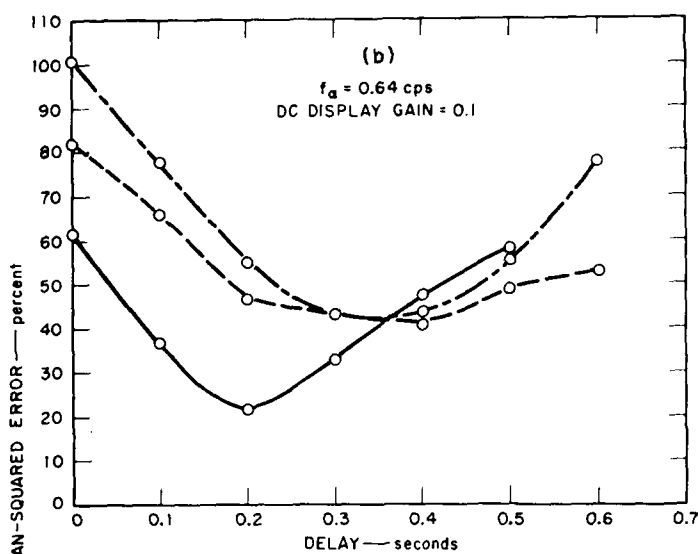
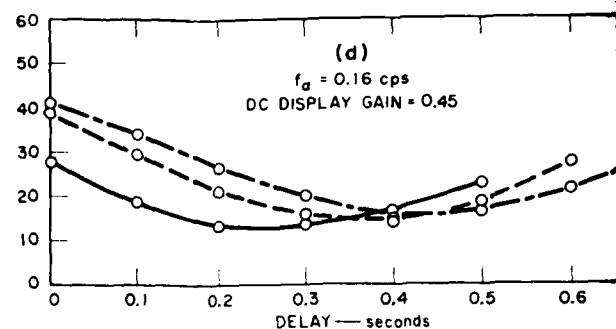
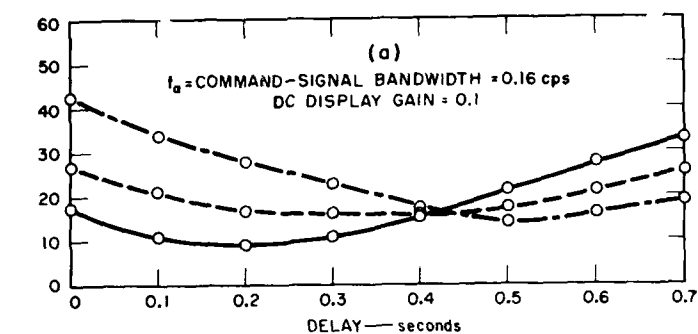
The same portion of each run was used. The computation was started exactly 15 seconds after the beginning of each run, and the integration was made over a 30-second period. This was repeated for the various values of delay.

Direct current levels in the tape recorder were particularly troublesome at first, and their effect on the results was quite serious as they were integrated over the 30-second period. Zero levels to which the playback amplifiers could be adjusted were therefore recorded each day. The gain settings of these amplifiers were also corrected before computation.

Only the x-axis response was analyzed, since it was felt that this response would give sufficient indication of the effects. In one case, however, where performance with the airjets was markedly better than that with the lights, the y-axis response was also analyzed. The results obtained are shown in Figs. IV-10 and IV-11. The display gain shown on these figures was actually a potentiometer setting on the computer and represents the d-c gain of the display. Table IV-1 relates these values

Table IV-1
DISPLAY GAIN FOR VARIOUS COMBINATIONS
OF DC DISPLAY GAIN AND COMMAND SIGNAL BANDWIDTH

Command Signal Bandwidth (cps)	DC Display Gain		
	0.1	0.45	0.80
0.16	3.53	15.9	28.2
0.64	7.06	31.8	56.5
1.05	8.25	37.1	66.0



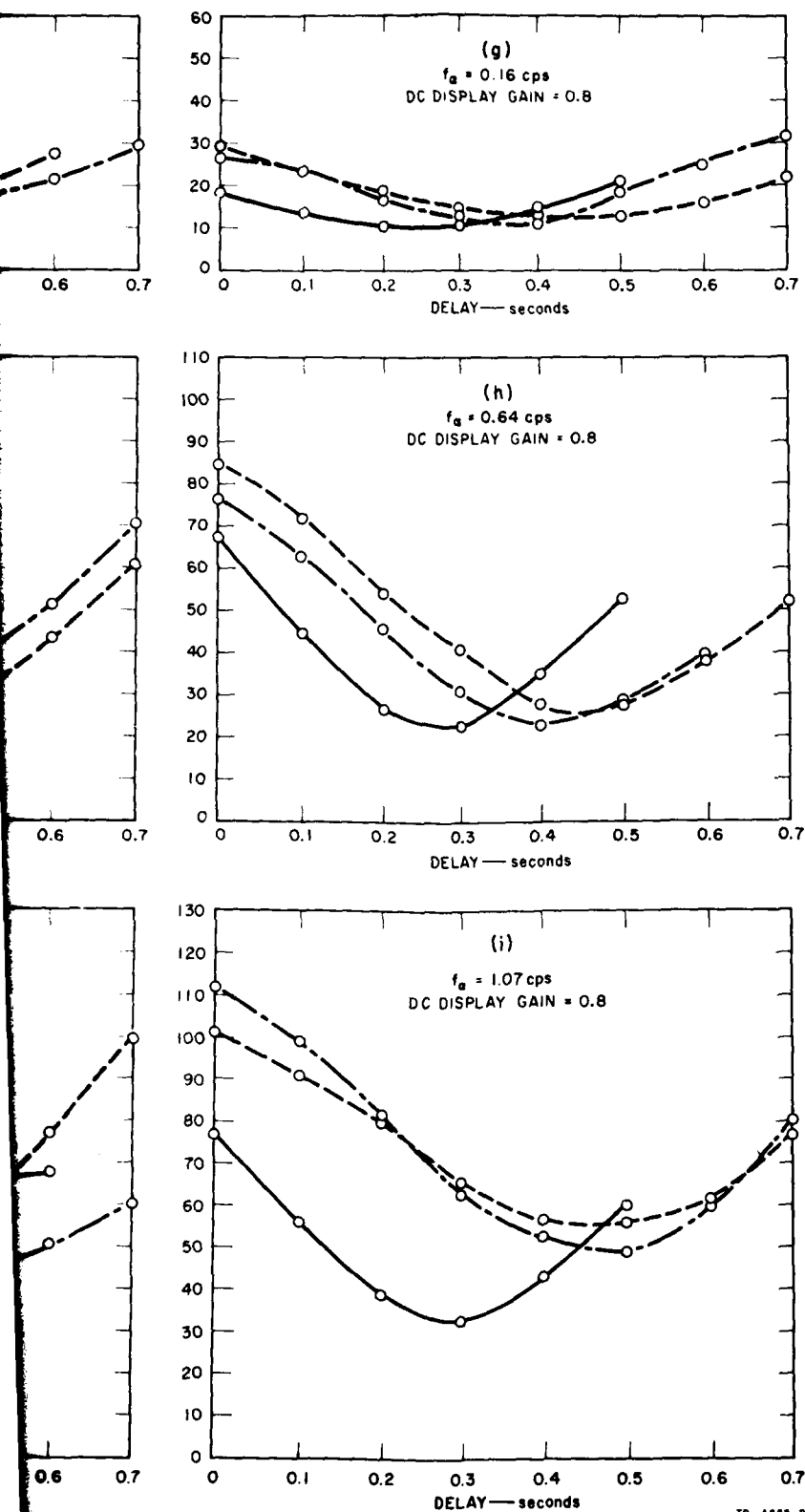


FIG. IV-10 X-AXIS PERFORMANCE AS A FUNCTION OF COMMAND-SIGNAL DELAY FOR VARIOUS DISPLAY GAINS AND COMMAND-SIGNAL BANDWIDTHS

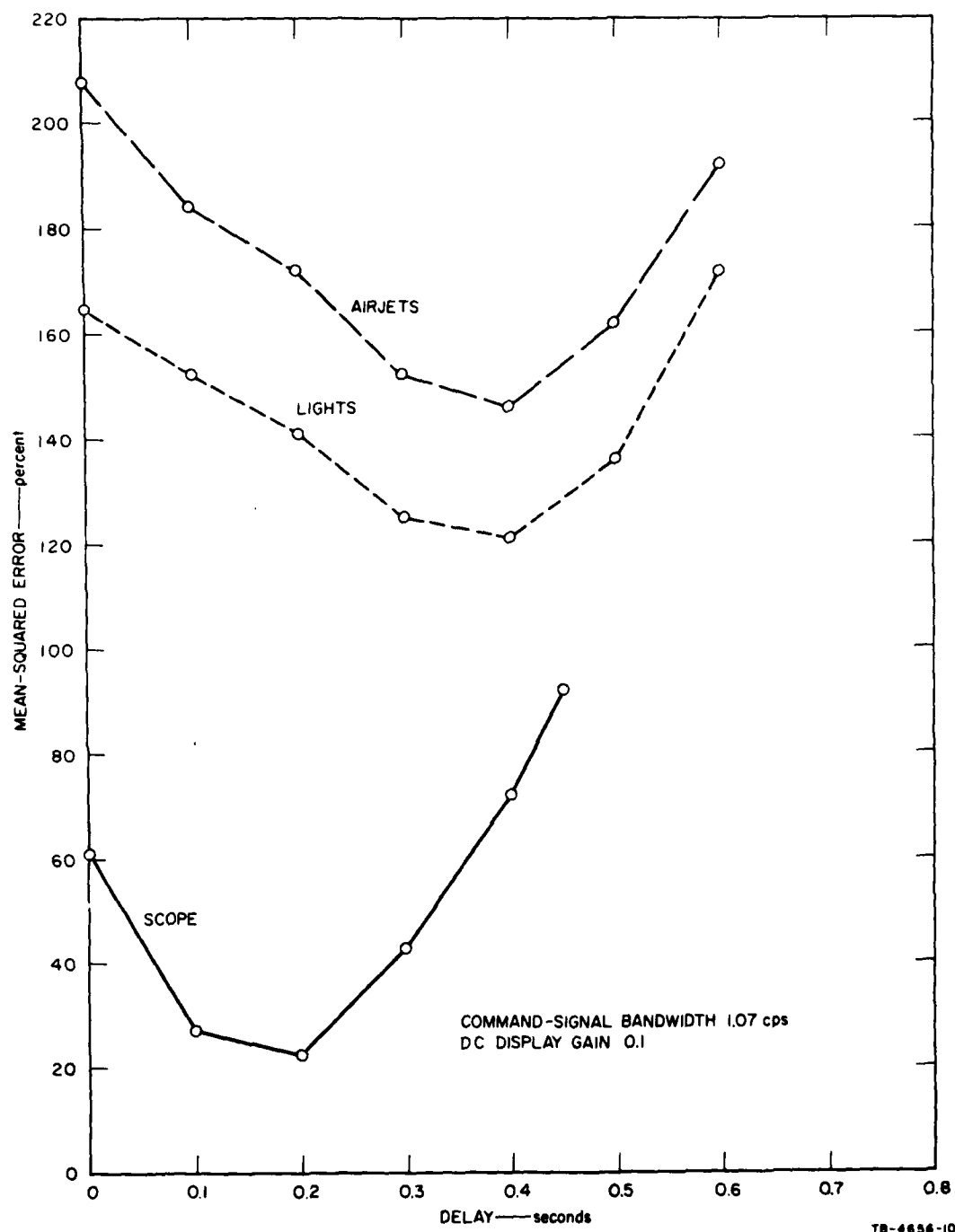


FIG. IV-11 Y-AXIS PERFORMANCE AS A FUNCTION OF COMMAND-SIGNAL DELAY

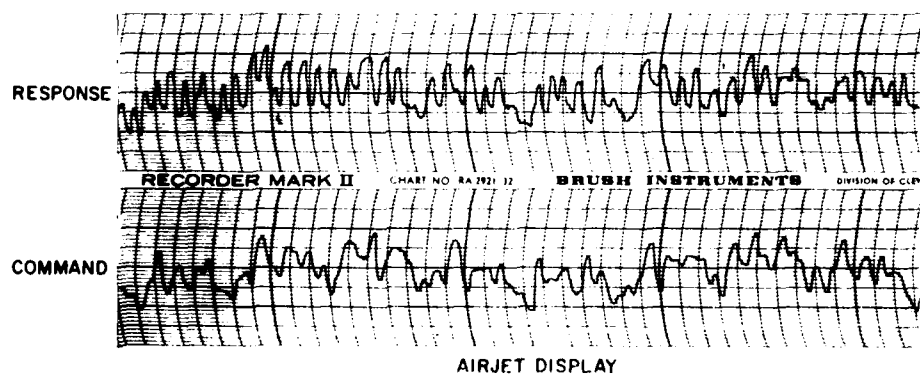
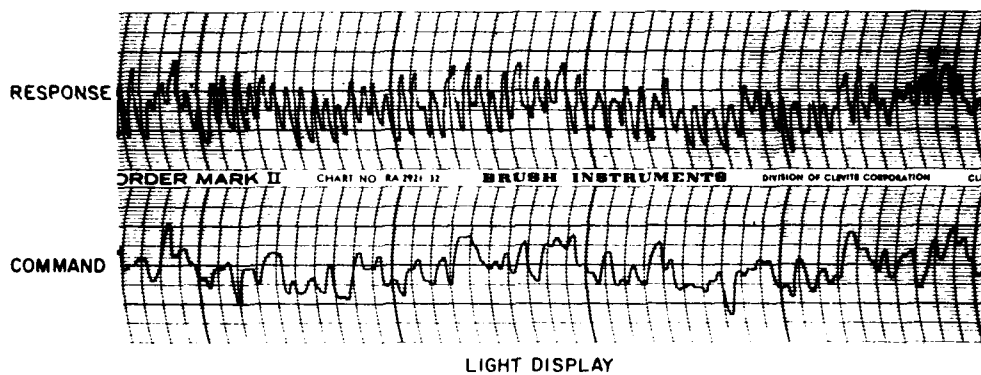
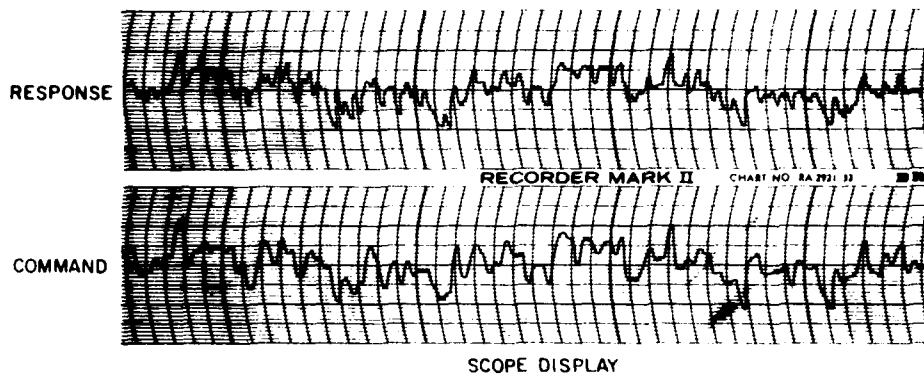
to the display gain defined earlier, that is, the ratio of the peak command to the signal for full scale on the displays. The three runs for each set of conditions have been averaged for clarity. Samples of the actual y-axis run for Fig. IV-11 are shown in Fig. IV-12.

For all nine combinations of display gain and cutoff frequency, each run shows a well defined minimum error for a delay of 0.2 to 0.3 second for the scope display, and 0.4 to 0.5 second for the quantized displays. Subsequent experiments could determine whether this difference is intrinsic to the human operator or merely an artifact introduced by the 150-msec sampling time of the quantizing instrumentation.

The error reduction factor, the ratio of integral squared error with no delay to that at the appropriate minimum, is greater at high cutoff frequencies, being as high as 2.5 in one case where a reduction from 95 percent to 38 percent was obtained. Assuming a pure delay in the operator transfer function, this phenomena can be explained by the presence of the higher frequency components in the command signal. Without the appropriate delay, the phase shift, and consequently the error, is greater for these components and therefore contributes significantly to the total error.

The error values for each run at the appropriate minima, averaged for each mode and plotted as functions of gain and cutoff frequency, are shown in Figs. IV-13 and IV-14. In the scope display, gain does not appear to have any great affect on the minimum error. For all three cutoff frequencies, however, the intermediate gain setting is the worst. It was pointed out previously that at high gains, tracking relies heavily on directional information, since the signal is theoretically off scale most of the time. Perhaps the intermediate gain setting offers neither the advantage of accurate magnitude information obtained at low gain nor the purely directional information obtained at high gain.

Most of the discrete mode runs show a reduction in error on going from low to intermediate gains, presumably because of the information lost by quantization at low amplitudes. In only one case is there an increase in error at high-gain settings, indicating once more the importance of directional information.



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FIG. IV-12 TYPICAL Y-AXIS RESPONSES
 filter corner frequency - 1.07 cps;
 display gain - 8.25

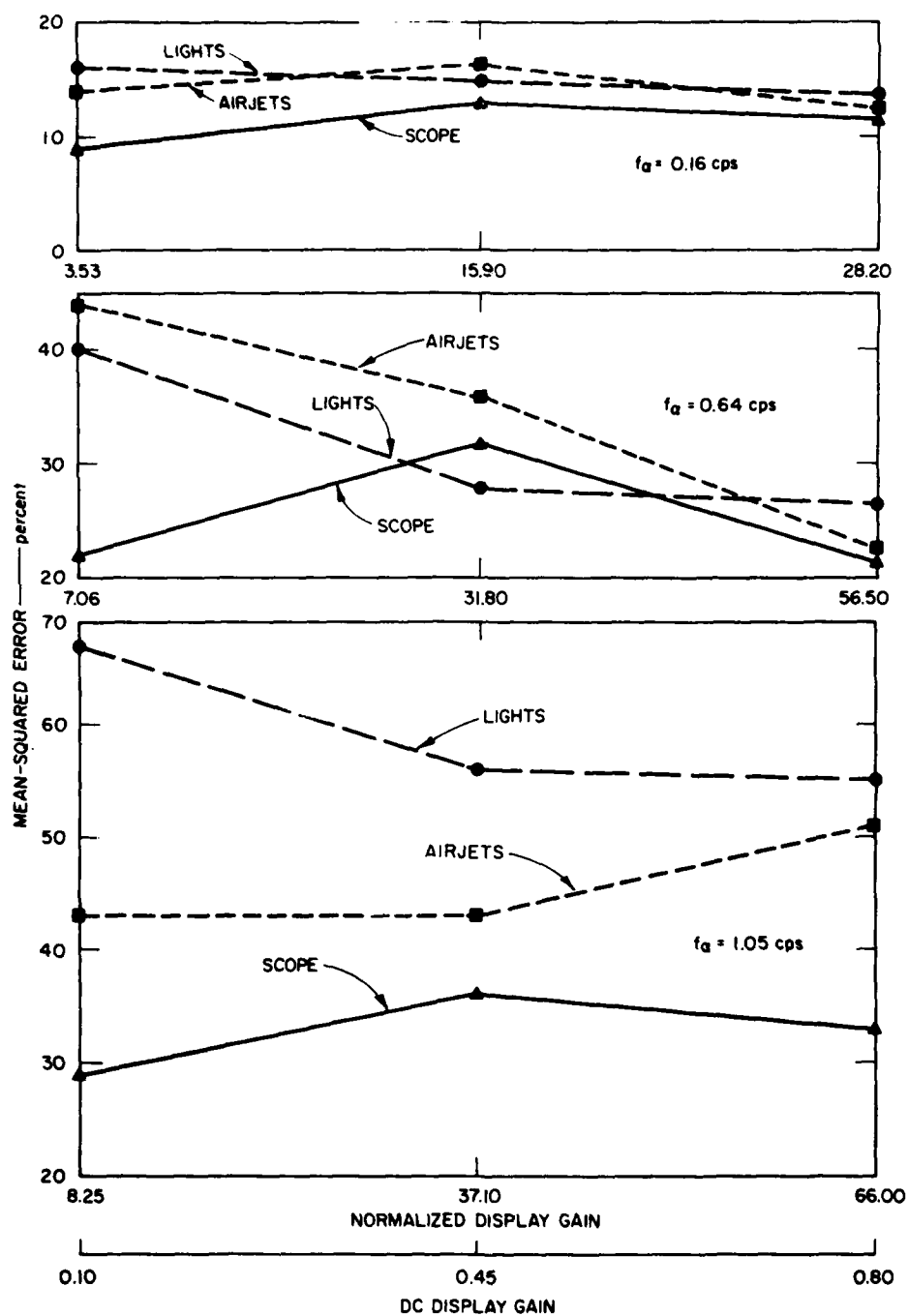
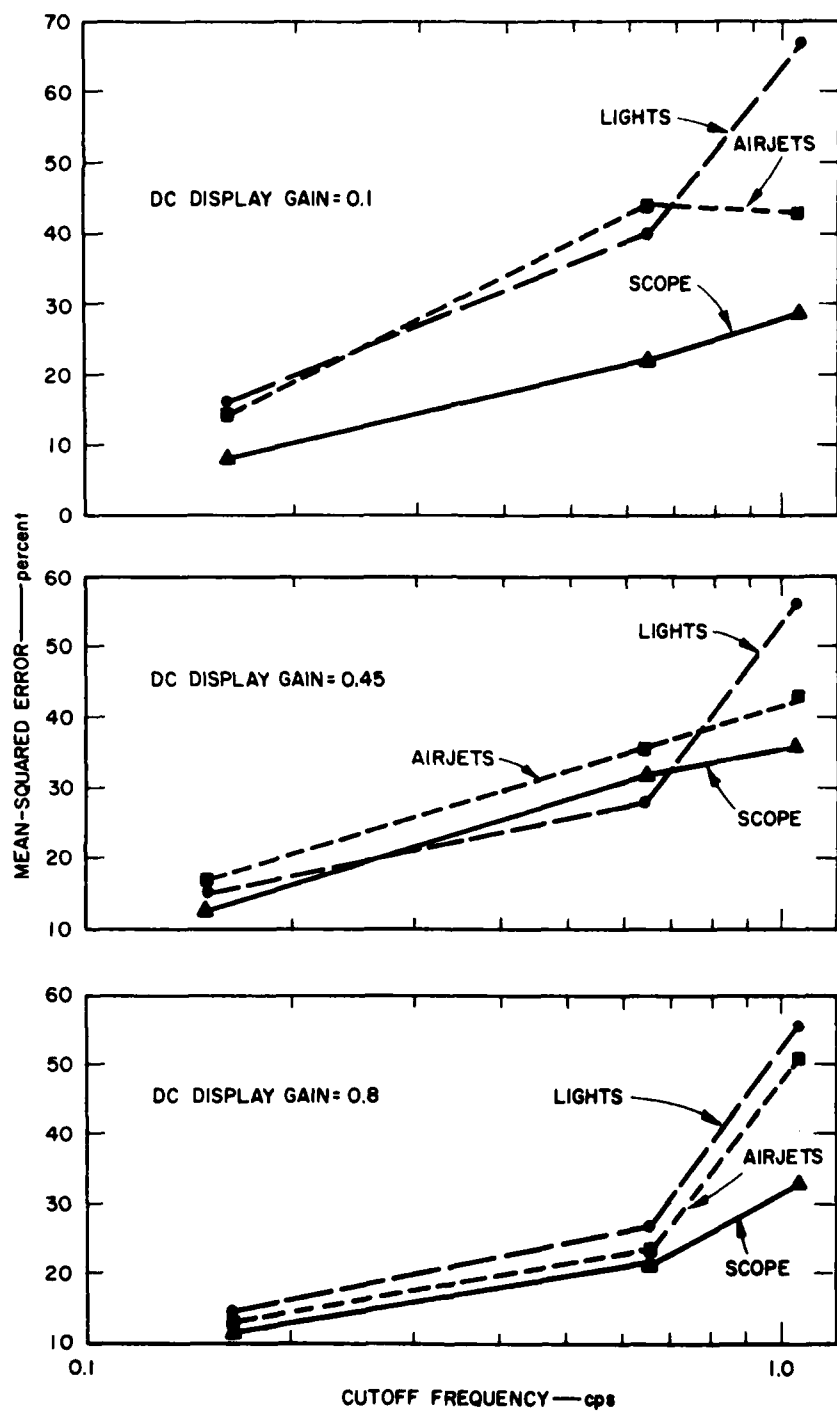


FIG. IV-13 MINIMUM MEAN-SQUARED ERROR VS DISPLAY GAIN



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FIG. IV-14 MINIMUM MEAN-SQUARED ERROR VS COMMAND-SIGNAL BANDWIDTH

All but one run show increasing error with cutoff frequency, the effect being more pronounced with the discrete displays.

It is interesting to note that with the appropriate delay inserted, the integral mean-squared error is generally below 50 percent and never exceeds 67 percent, showing that even at high gains and cutoff frequencies there is a significant degree of tracking.

In previous experiments (Fig. IV-4) it was observed that the error does not accumulate smoothly but in a series of jumps corresponding to peak values in the command signal. The effect of introducing the delay can be seen in Figs. IV-15 and IV-16. In Fig. IV-15, each curve shows the integral squared error as a function of time for various delays. The same 18-second section of a run recorded at high gain and cutoff was used, and the corresponding command signal is also given. The effect of the delay in reducing the size of the jumps is clear. The actual error (the difference between command and response) for the same section with no delay and with a delay of 0.3 second (the value corresponding to the minimum) is shown in Fig. IV-16. The error curve becomes much less "peaky", which has a very marked effect on the squared error computed before integrating.

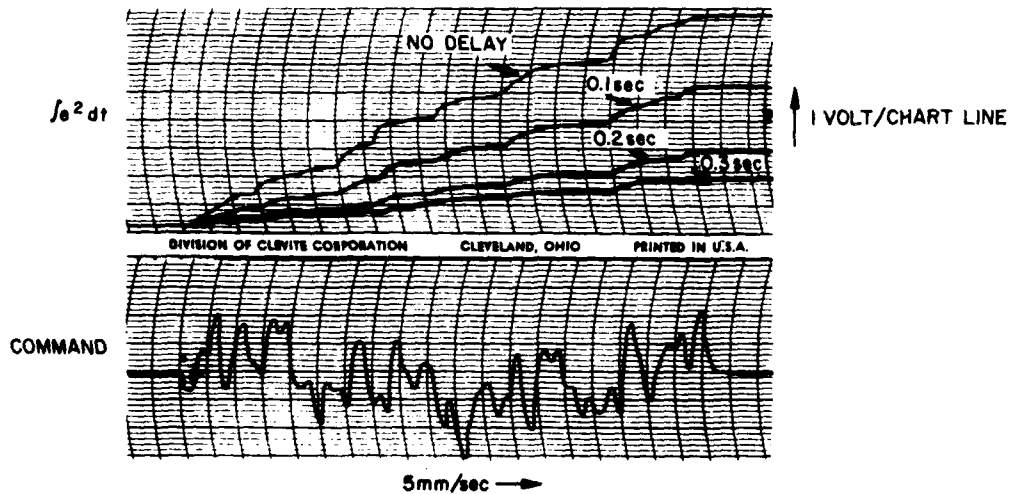


FIG. IV-15 INTEGRAL SQUARED ERROR VS TIME

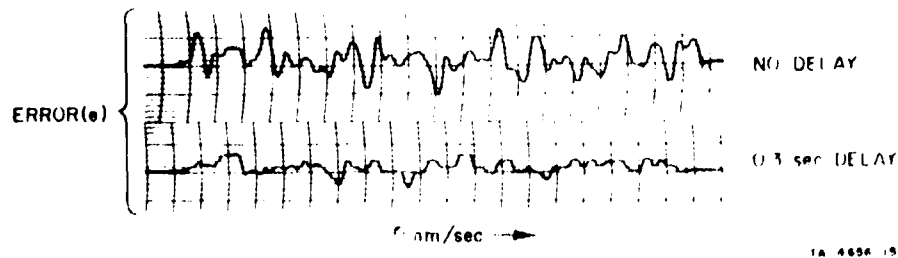


FIG. IV-16 ERROR WITH AND WITHOUT DELAYED COMMAND

F. Discussion

From a practical standpoint, performance with the tactile and discrete visual displays was approximately equal. Moreover, except for an additional delay that may be attributed to the time sampling of the error by the equipment, the minimum mean-squared error obtained with both discrete displays was not more than a factor of 3 higher than that obtained with the continuous visual display, under any of the display-gain and command-signal-bandwidth conditions. In fact, with low command-signal bandwidth and high display gain, minimum mean-squared error obtained with both discrete displays was almost equal (but delayed more) to that obtained with the continuous display.

Comparing performance with the tactile and discrete visual displays more closely, we find consistent differences as the display gain and command-signal bandwidth are varied. Performance with both discrete displays was remarkably equal for all three display-gain settings at the lowest command-signal bandwidth. Also, at the highest display-gain setting, minimum mean-squared error increased at an increasing rate with command-signal bandwidth for both discrete displays. Upon viewing these data in the matrix shown in Table IV-2, performance with both discrete displays was almost equal along the low command-signal-bandwidth row and the high display-gain column, but was increasingly different as the low display-gain and high command-signal-bandwidth condition is approached.

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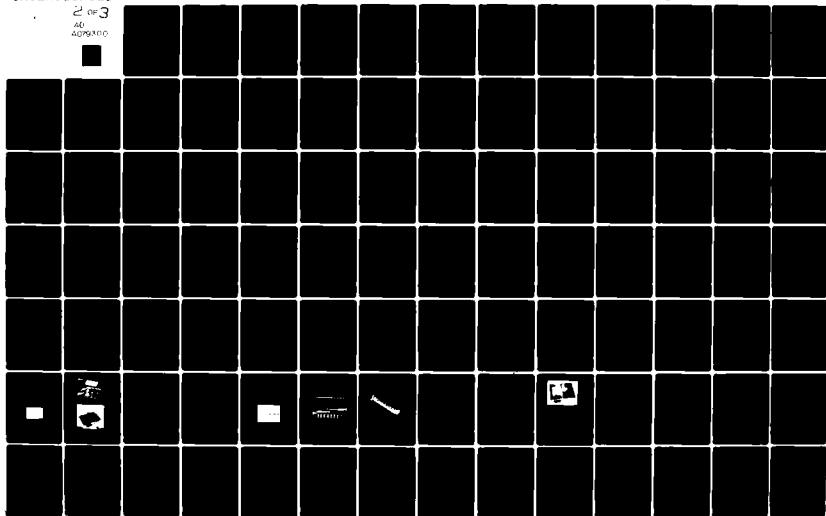


Table IV-2
MINIMUM MEAN SQUARED ERROR WITH THE DISCRETE DISPLAYS

Command Signal Bandwidth (cps)	DC Display Gain		
	0.1	0.45	0.8
0.16	14*	16*	13*
	16 ^φ	15 ^φ	14 ^φ
	(-2)	(+1)	(-1)
0.64	44*	36*	23*
	40 ^φ	28 ^φ	27 ^φ
	(+4)	(+8)	(-4)
1.05	43*	43*	51*
	67 ^φ	56 ^φ	55 ^φ
	(-24)	(-13)	(-4)

* Airjet display

^φ Light display

○ Difference

A possible interpretation of these results may be related to the improved magnitude information afforded by the anatomical reference given in the tactile display but not in the visual display. Recall that in the tactile experiments a center reference was maintained on the tip of the nose, but in the visual display experiments, no fixed center reference, such as a unique light, was provided. With this assumption, the discrete tactile display would be superior to the discrete visual display whenever detailed magnitude information is present, as occurs with low display gain and high command bandwidth.

To interpret the command-signal delay which resulted in a minimum of mean-squared error, note that the command signal $c(t)$ was a sum of sinusoids

$$c(t) = \sum_i c_i \sin \omega_i t \quad (IV-1)$$

where c_i is the magnitude of the i^{th} command-signal sinusoid and ω_i is the frequency of the i^{th} command-signal sinusoid. If it is assumed that the response $r(t)$ is a sum of the same sinusoids plus a remnant, then

$$r(t) = \sum_i r_i \sin (\omega_i t + \varphi_i) + n(t) \quad (IV-2)$$

Where r_i is the magnitude of the i^{th} response sinusoid

ω_i is the frequency of the i^{th} response sinusoid

φ_i is the phase of the i^{th} response sinusoid

and $n(t)$ is the remnant.

The analysis procedure was to delay the command with respect to the sinusoid and compute mean-squared error for each value of delay. Since this error $e(t, \delta)$ is given by

$$e(t, \delta) = c(t - \delta) - r(t) \quad , \quad (IV-3)$$

where δ is the delay, a minimum in mean-squared error implies that the following is identically zero:

$$\sum_i c_i r_i \omega_i \sin (\omega_i \delta_o - \varphi_i) = 0 \quad (IV-4)$$

where δ_o is the delay for minimum mean-squared error.

In any specific example, δ_o can be related to an assumed model for the human's transfer function. For example, if the transfer function for the human operator were simply a pure delay, then φ_i would be proportional to ω_i , so that Eq. IV-4 could be satisfied with every term identically zero, or $\delta_o = \varphi_i / \omega_i$, which is equal to the closed-loop transfer function

delay. With more complex models, however, each term in Eq. IV-1 would not be zero, and δ_o would generally depend on c_i , r_i , and ω_i , as well as ϕ_i .

The results of the experiments discussed in this section were incorporated in the design of the tracking equipment described in Appendix G.

V PHENOMENOLOGICAL OBSERVATIONS

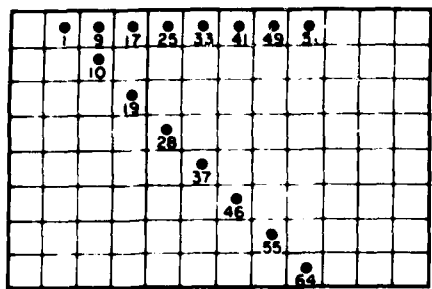
To build useful models we must assemble a great quantity of data. To a certain degree we can distinguish two kinds of data, qualitative (or phenomenological), and quantitative. Reliable, quantitative results are costly to obtain both in time and effort. Therefore, the experiments selected for quantitative analysis must be carefully chosen. To help make these selections, it is often useful to review the results of many simple short experiments (perhaps even those not very well controlled), in which the responses are highly subjective.

In this section we will give some examples of this type of subjective, qualitative experiment. There is little past experience on which to base experiments involving perception of a large array of stimulation points. The experiments given here were primarily attempts to obtain insight into the types of responses to expect from pattern stimulation. There was thus no attempt to be quantitative, and there is no special scheme or order to the presentation. In Section VI we present the results from some quantitative experiments.

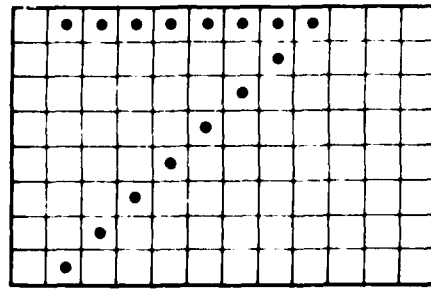
The members of this project were the subjects in these qualitative experiments. None had any significant previous experience as subjects in tactual psychophysical experiments of this type. The patterns were generally presented on the forehead or fingers. The general approach in these experiments was to present the subject with a pattern and ask him to describe the perceived pattern by drawing a sketch. As we will see, when the subject is presented with an unknown stimulus pattern, the perceived patterns can vary widely. We will not attempt to report all the forms of response, but will highlight some of the more obvious features. The stimulus patterns discussed in this section are shown in Fig. V-1.

A. Modes of Presentation

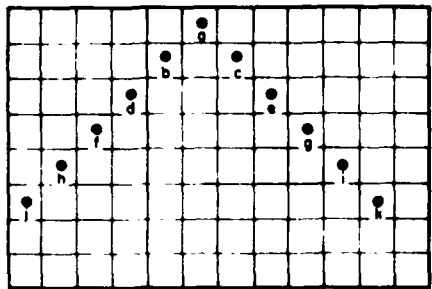
Three different modes of presentation were used in these experiments: (1) point scan, (2) line scan, and (3) frame scan. (See the glossary and



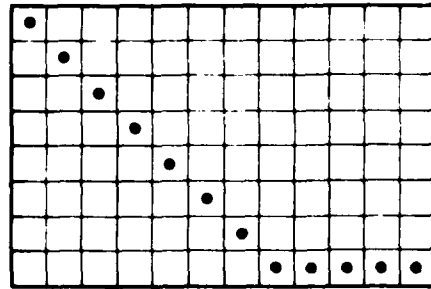
A



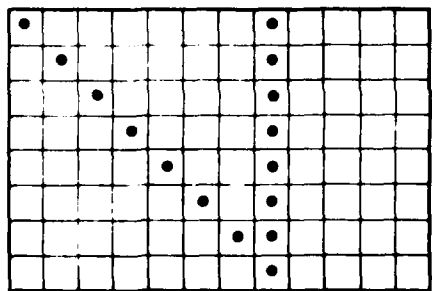
B



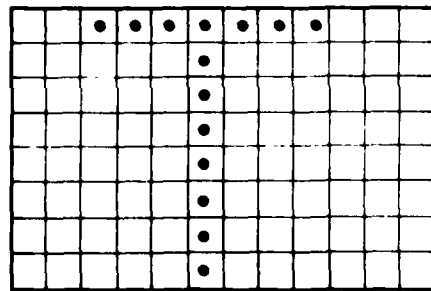
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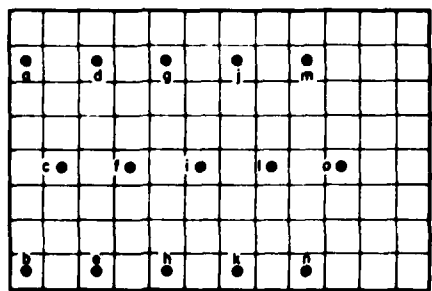
D



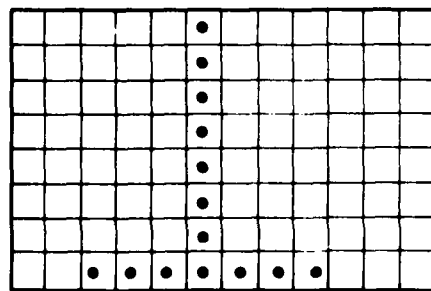
E



F



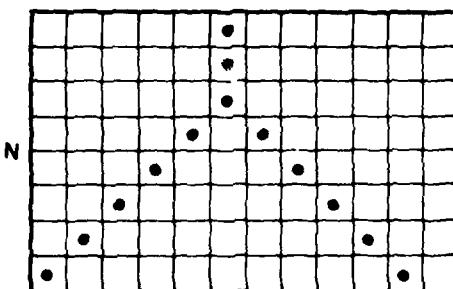
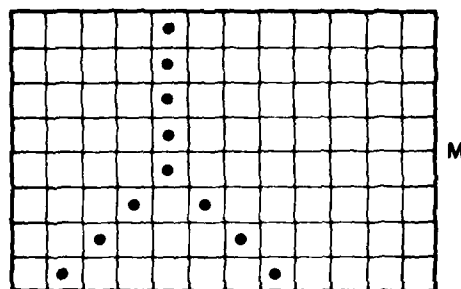
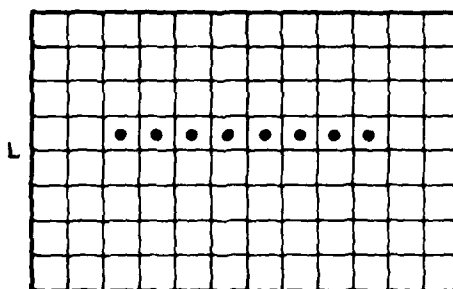
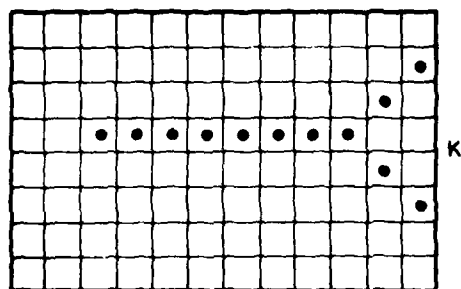
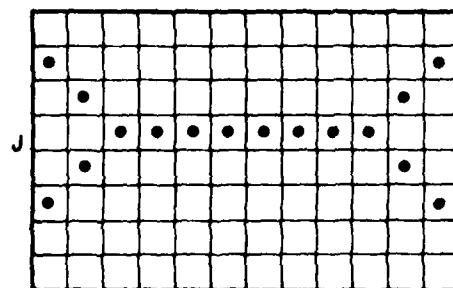
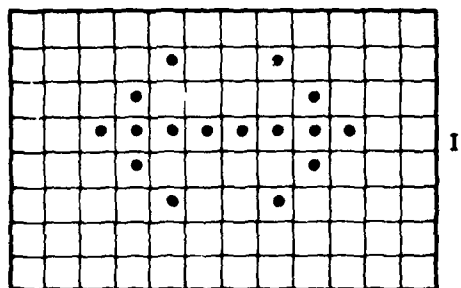
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FIG. V-1 STIMULUS PATTERNS



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FIG. V-1 Concluded

Appendix E for discussion of these modes.) All the experiments commented on here were run at a basic rate of 25 milliseconds per step. To "point scan" an entire pattern at this rate would require (25×96) , or approximately 2.5 seconds. To "line scan" an entire pattern would take only (25×8) , or 0.2 second.

As to the duration of stimulation, there are two possibilities, referred to as "line reset" and "frame reset." With line reset, each row of stimulators is cleared before the next row is energized. Hence, in line scan mode with line reset, all of the energized stimulators in one row are cleared before the next row is energized. In point scan with line reset, only a single stimulator can be energized at a time.

With frame reset, all triggered stimulators remain energized until the pattern is completely scanned vertically. Thus, where a single vertical-line pattern is presented with frame reset in line scan mode, the triggered stimulator in the appropriate column of the first row remains energized for eight units of time, the stimulator in the second row of the same column remains energized for seven units of time, and so on until in the bottom row, the stimulator remains energized for only a single unit of time. In other words, all stimulators are reset simultaneously, but they are energized progressively. This mode of reset is not often used, and unless otherwise stated, line reset should be assumed.

With point scan and frame reset, the same holds true for each column. In other words, it takes twelve vertical scans to point scan an entire pattern. The first time through, only the first column of stimulators is energized; the second time through, the second column is energized, and so on until the twelfth time through, when the last column is energized. Thus, the mode of presentation would be the same whether a vertical line were point scanned or line scanned. For a horizontal line, however, presentation would be very different. On line scan all points would be presented simultaneously, whereas on point scan they would be presented one at a time starting from the left.

B. Apparent Position

From previous results with apparent-position experiments (Kotovsky and Bliss, 1963) we speculated that perception might be different when scanning an angle toward its apex than when scanning it away from its apex. This proved to be so. Patterns A and B (Fig. V-1) were used to test this notion. Consider a point-scan presentation of the first pattern. To be sure that the method of scanning is clear, we will consider the timing of the stimulators. The top left stimulator is energized first, let us say at time interval 1. The scanning point moves vertically downward but finds no other stimulators to be energized in this column. Eight units of time later, or at time interval 9, the stimulator marked 9 is energized. As the scanning point moves vertically downward, it immediately encounters the next stimulator and energizes it at time 10. As the scan reaches the top of the third column, at time interval 17, it energizes that stimulator, and so on.

When pattern A was presented in this fashion, on the hand or forehead, the resulting sensation had the form sketched in Fig. V-2(a). Points 9 and 10 are sufficiently close in space and time to be perceived as a single point between them; the same was true for points 17 and 19. In other words, a certain number of columns must be scanned before the single "apparent-position" line is perceived as two separate lines.

On the other hand, pattern B was easily perceived as two separate lines converging toward an apex, although the region near the apex often appeared curved, as indicated in Fig. V-2(b), or even more potbellied, as in Fig. V-2(c). The angle was generally perceived as being considerably less than 45 degrees.

When either pattern A or pattern B was presented with frame reset, the horizontal line remained energized longer and felt considerably stronger than the other line forming the angle.

The same apparent position effect resulted when the 90-degree angle of pattern C was line scanned so that point a was presented first, then points b and c simultaneously, followed by points d and e simultaneously, and so on. The pattern was often perceived as a single line extending part way down the middle and then separation into two distinct lines.

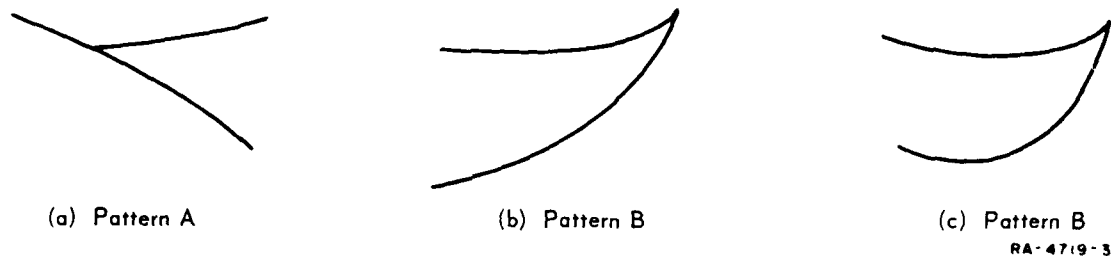


FIG. V-2 SKETCHED RESPONSES TO PATTERNS A AND B

C. Losing Corners

In general, we have found that corners are perceived as rounded. For example, pattern D, with either point scan or line scan, was generally reported as a straight sloping line or a line with a bit of rounding on the end, as sketched in Fig. V-3(a). Pattern E, whether presented in line scan or point scan mode, was also often reported as rounded, as suggested in Fig. V-3(b).

We have not yet determined whether with training and learning, a corner can be sensed as a corner. In any case, on the basis of these results it was suspected that a letter "T" (pattern F) presented in point scan might be sensed as shown in Fig. V-4(a). In this scan mode, the left portion of the horizontal line was presented first, followed by the vertical line. It was thought that this 90-degree segment might be



FIG. V-3 SKETCHED RESPONSES TO PATTERNS D AND E



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FIG. V-4 SKETCHED RESPONSE TO PATTERN F

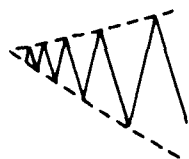
sensed as curved, as suggested, with the right section tacked on. The resulting impression was indeed of this form, except for the perception of an additional line, as shown in Fig. V-4(b), which felt very much like a "retrace line." The sensation of a retrace line is caused by the apparent motion phenomenon.

D. Apparent Motion

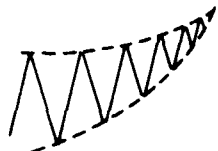
The perception of apparent motion depends upon there being certain time delays between the excitation of different stimulators. (The reader is referred to Kotovsky and Bliss, 1963 for details about the range of delay required as a function of separation of the points.) Generally, 50 to 150 msec delay between the excitation of two stimulators, say an inch apart on the forehead, will give a strong impression of apparent motion.

Apparent motion can occur with line scan as well as point scan. For example, consider a pattern of only two stimulator points separated by five lines in the same column. In this case, the presentation in point scan mode will be identical to that in the line scan; the second point will appear (6×25) or 150 msec after the first (assuming a scan rate of 25 msec per vertical position), and a strong apparent motion effect will be felt with either mode.

Although apparent motion effects occur with both types of scan, they are generally more common with point scan. To see why this is so, consider pattern G, which can be thought to consist of three horizontal lines. With line scan, the impression is essentially just that--three



(a) Pattern A



(b) Pattern B

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FIG. V-5 SKETCHED RESPONSES, SHOWING EFFECTS OF APPARENT MOTION

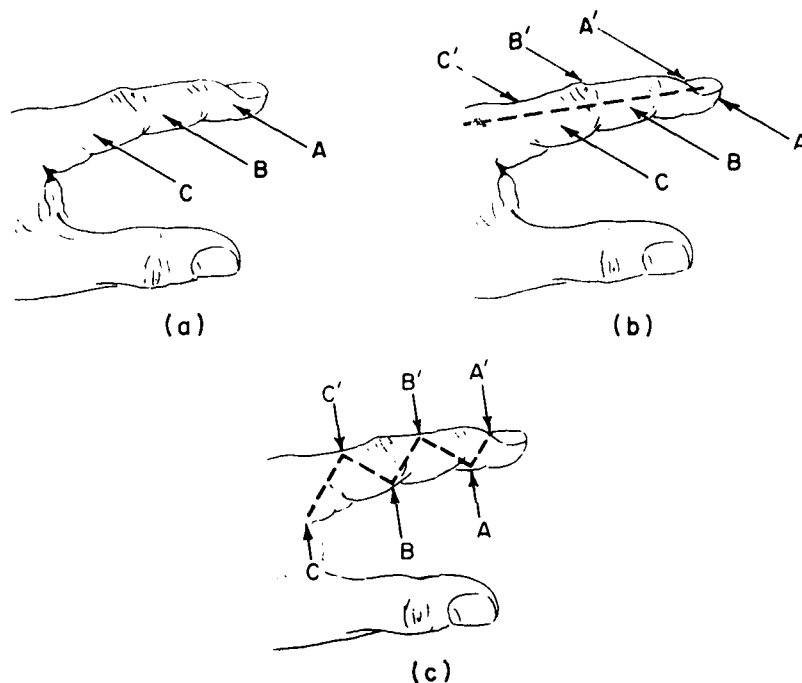
horizontal lines. During time interval 2 (corresponding to the second row), the first horizontal line is presented; during time interval 5, the second line is presented; and during interval 8, the third line is presented. With line scan there is essentially no perception of apparent motion. With point scan, however, the pattern is presented in the order indicated by the alphabetical labelling of the points. Point a is presented first. Six intervals of time (or 150 msec) later point b is presented, and a strong apparent-motion line is sensed. Five intervals of time (or 125 msec) later, point c is presented, giving an additional apparent-motion effect from point b to point c. After another 125 msec, point d is presented, so that there appears to be a continuous line of motion from point b to point d. Often, then, this presentation results in the perception of a saw-tooth pattern consisting of vertical lines and sloping interconnecting diagonals. By "often" we mean that one does not perceive the same pattern each time; there are effects of learning and "selective perception," which are discussed in later sections.

We might note that the sketches of Figs. V-2(a) and (b) really represent the envelopes or outlines of the actual perceptions. The more usual perception report includes apparent motion effects, as indicated in Figs. V-5(a) and (b), which correspond to patterns A and B, respectively.

E. Three-Dimensional, Apparent-Motion Effects

Although apparent-motion effects can be obtained with just two stimulators, the effect is considerably improved when three stimulators are energized in sequence, e.g., the stimulators A, B, and C in Fig. V-6(a). It was interesting to speculate whether apparent-position and apparent-motion effects could be combined to give a sort of volumetric sensation, i.e., a line of motions felt within rather than on the body surface. To

test this notion, apparent-motion stimuli were simultaneously presented to two sides of a finger, as illustrated in Fig. V-6(b). The sensation was indeed that of a broadened line traveling through the center of the finger. If the stimulators were offset spatially and energized sequentially, then the effect was that of a zig-zag line running through the finger, as shown in Fig. V-6(c).

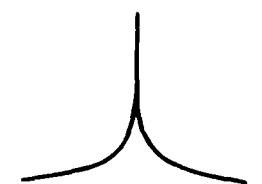


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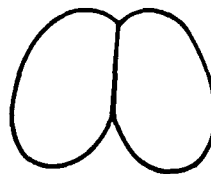
FIG. V-6 STIMULATION FOR VOLUMETRIC PERCEPTION

F. Repetitive Presentation

In addition to perceptual patterns achieved from presentation of a single pattern, other effects can be achieved if this same pattern is presented repetitively in rapid sequence. For example, a response to pattern H, presented a single time in line scan mode, is sketched in Fig. V-7(a). It is interesting that even though the points of the bottom horizontal line are presented simultaneously, the overall perception is one of two curved sections extending from the initial vertical line.



(a) Single Presentation



(b) Repetitive Presentation

RA-4719-3D

FIG. V-7 SKETCHED RESPONSES TO PATTERN H

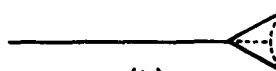
This effect agrees with the results already indicated in the discussion of "losing corners." In any case, if pattern H is repeated rapidly a number of times, then the perception changes to that shown in Fig. V-7(b), in which strong retrace lines appear, the overall pattern being one of smooth, continuous lines, as shown.

G. Illusions

Patterns I and J were used to test the tactual response to these familiar optical-illusion patterns. After one became familiar with these patterns on the skin, the horizontal line did indeed feel shorter in the more compact pattern I. In pattern J, a typical response on line scan was that the ends were curved, as indicated in Fig. V-8(a). This result led to the speculation that if a curved end fits within the actual triangular region of the stimulus pattern, as suggested in Fig. V-8(b), then the horizontal line might appear to be lengthened. To test this effect,



(a)



(b)



(c)

RA-4719-4

FIG. V-8 SKETCHED RESPONSE TO PATTERN J

the patterns K and L were used, K being the same as pattern J except that it was simplified by elimination of the left end. Pattern L is simply a horizontal line of exactly the same length as the horizontal portion of pattern K. The result was as expected; the horizontal line appeared longer in pattern K, apparently being lengthened by the curved end, although sometimes the section of line close to the curved end appeared somewhat weaker than the more removed portions of the horizontal line.

H. Ambiguity and Learning

Often, initial responses to an unknown pattern hardly resemble the actual stimulus. For example, Figs. V-9 and V-10 show some of the exact initial responses to patterns I and J, respectively, which were presented in point scan mode. Note the apparent-motion effects indicated by the sketched-in, saw-tooth lines. Before the subject was informed what the patterns actually were, they were so undefined in his mind that he could hardly tell one from the other, and if an actual test had been run, he

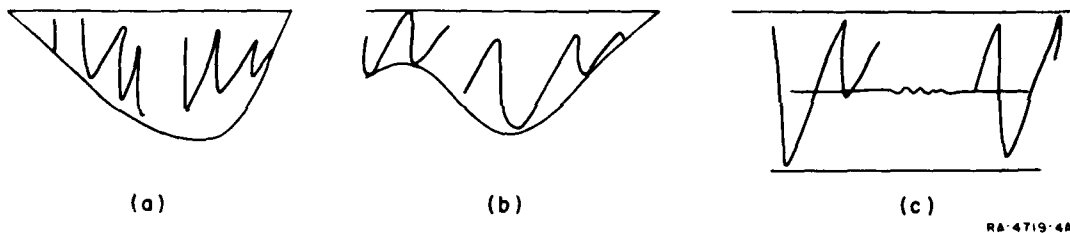


FIG. V-9 INITIAL SKETCHED RESPONSES TO PATTERN I

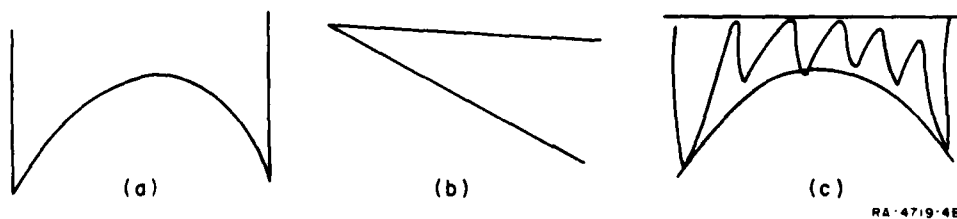


FIG. V-10 INITIAL SKETCHED RESPONSES TO PATTERN J

probably would have scored poorly on a forced-choice experiment in which the two patterns were shown over and over in random sequence. After being shown the stimulus patterns, however, he could immediately "see" the pattern as that being presented; but, more important, in the same hypothetical forced-choice experiment with just these two patterns, he would probably have scored 100 percent (although, again, no test was actually run).



FIG. V-11 INITIAL SKETCHED
RESPONSES TO
PATTERN M

Actually, the same results are obtained with most patterns, even the "simpler" ones, such as the inverted Y (pattern M). Some initial responses to this pattern, presented in line scan mode, are sketched in Fig. V-11.

I. Selective Perception

We are all familiar with the type of three-dimensional optical illusion in which a pattern can be perceived from either one perspective or its inverse. This type of "selective perception" was noted during the initial tactual experiments. For example, during stimulation with the inverted V (pattern C), if a subject tried to be as objective as possible about what he felt, then even though he knew the exact pattern being presented, he would draw the sketch shown in Fig. V-7(a). However, if he introspected, with some thought such as, "I know they are straight lines, why don't I feel it that way?" he would "force" himself to feel a good straight-line version of the stimulus pattern. If he then tried to "shake the thought out of himself" and become "objective" again, he would sense the original curved pattern.

J. Discussion

The qualitative nature of the material in this section should leave little doubt that the results are only preliminary. The purpose of presenting them is simply to relate a range of diverse subjective observations. Hopefully, these observations will be explainable on the basis of models derived from more quantitative studies.

VI QUANTITATIVE STUDIES

A. Introduction

In this section we will report the results of three studies which are more objective and quantitative than the very subjective experiments of the previous section. The first experiment was motivated by results from the study reported in Section III, in which it was noted that there was considerable improvement in performance with the moving Times Square display than with the static frame presentation. The study reported here is a quantitative study of the effect of deliberate pattern "jitter," or movement, on performance. The results indicate conclusively that movement significantly improves performance. From an analysis of variance we see that the results are statistically significant, and we find an empirical relation between frequency of rotational movement (amplitude remaining fixed) and stimulus presentation time.

The second study was motivated primarily by tracking studies, particularly methods of displaying an analog quantity. This study was concerned with the accuracy with which a single analog quantity could be transmitted tactually, and, more particularly, the effect of a number of different presentation methods. For each method of presentation a confusion matrix was obtained, which was analyzed by information theory techniques to derive an expression for the number of bits per presentation. Depending on the presentation method, from 1.3 to 2.1 bits per presentation were obtained, which quantitatively illustrates the relative advantage of certain methods. The highest magnitude of bits per presentation obtained is in the same range as that obtained for vision and audition when only a single stimulus dimension is varied.

During the past ten years the theory of signal detection has made important contributions to our understanding of man's ability to detect and recognize acoustic signals (Swets, 1964). However, there has been little application of this theory to the study of tactual perception, although Eijkman and Vendrik (reprinted in Swets, 1964) obtained interesting results in the study of "amplitude" discriminations for the

sensations of touch and warmth. In the third quantitative study reported here, we wished to investigate the feasibility of applying the theory of signal detection to a study of man's ability to discriminate between different loci of tactual stimulation. We found that the theory of signal detection does predict the results and that the results of these limited studies are sufficiently promising to warrant further investigation of the theory of signal detection as a potential tool for increasing our understanding of tactual perception.

B. Effect of Stimulus Pattern Movement

It was noted in Sections II and III that there was a considerable improvement when the relatively complex capital-letter forms were made to move across the skin in the Times Square mode. But there is only a finite range of propagation velocity over which a smooth sensation is felt and an improvement is achieved. If the velocity is too slow, the perception is simply that of a letter being presented a number of times in different positions, and there is no overall improvement. Too high a velocity, and performance again deteriorates, partly because the total presentation time is too short.

To study this spatial-temporal interaction further, it was decided to use a different mode of stimulus pattern movement, namely a small circular translation (or nutation). In this mode, the entire pattern is simultaneously translated about a small circular locus (compared to the size of the array), so that each activated jet follows a circular locus on the skin. By changing the diameter of the circular path, the velocity of the rotational motion, or the frequency of the air jets, we obtain a fairly wide range of parameter conditions. Except for a slight increase in the excited area because of the movement, the pattern remains fixed over the same anatomical position. Thus, we can readily get a measure of performance with and without motion over the same position.

There were three other reasons for interest in this particular stimulus movement. First, it is reminiscent of vibrations in the eye, which are important for continuous vision. It is well known that if these eye vibrations are effectively cancelled, as in "stabilized image"

experiments, then vision rather quickly fades. Moreover, Krauskopf (1957), who introduced controlled motion in visual stabilized-image experiments, reported some improvement in acuity for oscillations at frequencies below 10 cps and of sufficient amplitude.

Second, if one tries to read lettering through a piece of shattered glass, where the average size of the intact glass is smaller than the letter size (e.g., through the ends of a stack of microscope slides), then significant improvement is achieved simply by vibrating the shattered glass in its own plane. In this way the distortion introduced by the fine structure of the shattered glass is averaged out. (Less improvement is obtained if the source material is vibrated instead of the glass.) For our tactual perception experiments it was felt that since the overall tactual pictures are not more than a half-dozen or so two-point limen distances (i.e., close to the limit of spatial resolution on the skin), then the effects of distortion introduced by nonuniform afferent receptor fields might similarly be averaged out by vibrating the pattern over the skin.

Thirdly, there is some neurophysiological evidence which suggests that tactual perception should be improved with pattern vibration. For example, from a study of cortical recordings, Mountcastle (1957, page 410) observed:

"It is a common observation quickly confirmed that tactile sensation is more acute if the exploring finger pad moves lightly over the test surface than if held motionless against it--for example, in differentiating fine grades of sandpaper, in the finger movements of the blind in reading Braille, or in assaying the quality of cloth. Oscillatory movement of the sensory receptor sheet will produce sharper peaks in the grid of cortical activity, with steeper gradients between them. Temporal alternation in the activity of two widely overlapped groups of cells will accentuate the role of refractoriness of those cells common to both, rather than spatial facilitation, thus greatly steepening the gradients of activity between the two peaks."

Four experiments were performed as described below.

- (1) The first experiment was strictly exploratory. A subject who had been trained on the Times Square display with the

special alphabet was presented the same characters statically (i.e., in the frame mode) and an attempt was made to see if display movement would aid in perception. The subjective results were definitely positive.

- (2) In the second experiment a new subject was trained on the special alphabet. During the training sessions the static and "jittered" patterns were used alternately. The quantitative results clearly showed an advantage with the "jittered" mode.
- (3) The results from the second experiment were sufficiently positive that a third experiment was performed to obtain a more quantitative study of the effects of stimulus-pattern presentation time and pattern rotation frequency. An empirical relation among performance, presentation time, and rotation frequency was determined.
- (4) In the fourth experiment, the effect of stimulus-pattern rotation amplitude was studied.

To vibrate the display, a simple variable-speed motor pulley system was built. The display speed could be adjusted between 0 and 1500 rpm, and the coupling between the motor and display could be varied so that the diameter of the rotational motion of the display could be adjusted between zero and 4 cm. The spacing between the jets in the display was 1/4 inch. For these experiments the air jets were all synchronized and their frequency adjusted to 200 cps. The subjects suspended their right middle fingers and forefingers over the matrix, with the arm and palm of the hand supported by a rest.

The three subjects used in the experiments were recent high-school graduates, who appeared to be of above-average intelligence and unusual calmness in the testing situation.

The specially designed alphabetic symbols shown in Fig. III-3 were used as the stimulus pattern in all experiments except Experiment 4. In Experiment 4, rotation amplitude, the block letters shown in Fig. II-4 were used.

1. Experiment 1--Exploratory*

The first moving-stimulus experiment was of an exploratory nature and was performed on Subject 4 (S4). The purpose was to obtain a

* This experiment was performed and reported by K. Kotovsky.

subjective appraisal, by the subject, of the value of moving the letters upon presentation versus the value of a snapshot "frame" presentation in which the letter does not move relative to the skin. An attempt was also made to obtain an idea of the effects of different amplitudes and frequencies of motion. The presentation consisted of a letter of 1/2-second duration, a space of 1/2-second duration, a letter, and so on. The average letter presentation rate was therefore 1 letter per second. The subject had been thoroughly trained (20 hours) on the Times Square presentation of the specially-designed letter alphabet (see Section III, Fig. III-3). The results of this experiment are presented in Table VI-1. A conclusion from this table is that the subject generally preferred a certain amount of motion, and that the larger the diameter of the vibration the lower the optimum rotation velocity. The subjective report was that motion presentations at the "good" or "best" settings were much preferable to the no-motion presentations. This preference did not, however, result in improved performance in the tests described below.

At the end of Experiment 1 the subject's ability to "read" random letters was tested for one minute with static-frame presentation and for one-minute with motion presentation at an amplitude of 0.9 cm and a display speed of 900 rpm. No significant difference in the performance was noted between the two modes of presentation. The amount of testing was, however, necessarily minimal because of time problems. Two of the experimenters noted (as did the subject) that when a letter was presented with motion, it felt solid, unmoving, and "stronger" than when presented without motion.

Table VI-1
SUBJECTIVE REPORTS ON VARIOUS CONDITIONS OF STIMULUS PATTERN MOVEMENT

Diameter of Rotation	Best	Good	Poor (unintelligible letters)
0.3 cm	> 1500 rpm	< 1500 rpm	--
0.8 cm	900 rpm	> 300 rpm	< 300 rpm
1.3 cm	250 rpm	--	> 1300 rpm
2.5 cm	120 rpm	120-900 rpm	> 900 rpm

2. Experiment 2--Learning and Response Factors*

The results of the first exploratory experiment prompted the undertaking of a more extensive series of experiments with a new, untrained subject (S9). The first of these experiments was concerned with the effect of motion on the ability of a tactually naive subject to learn to read symbolic letters from the airjet matrix.

a. Sessions 1-21

Learning and testing sessions of approximately one hour's duration were conducted with Subject 9. The first session was concerned with ascertaining that the subject had learned (from flashcards) the symbolic alphabet perfectly (100 percent on three trials), and with his picking out what felt like a "good" frequency and amplitude of rotational motion of the matrix.

The frequency and amplitude selected were 0.8 cm and 14 revolutions per second. The duration of a single exposure frame was 0.3 seconds. (Thus, approximately four rotations occurred during each frame.) For Sessions 2 through 9 there were five empty frames, or 1.5 seconds between letters, during which time the subject called out the letter he had just received. This spacing corresponds to an overall letter rate of 1.8 seconds per letter. In Sessions 10 and 11 there were only three empty frames between letters, and in Sessions 12 and 13 there were only two, making the effective letter presentation rates in these sessions 1.2 and 0.9 seconds per letter, respectively. The subject's responses were checked against a master list of responses by the experimenter. The letter sequences were changed for each test.

After Session 1, a protocol which outlined the course of the experimental hour-long sessions was initiated. The protocol (Table VI-2) interspersed testing and learning periods with rests to minimize fatigue.

* This experiment was designed and reported on by K. Kotovsky except for Sessions 36-53.

Table VI-2
 PROTOCOL FOR STIMULUS MOVEMENT EXPERIMENTS

Repeated three times	Operation	Duration (minutes)	Explanation
	Stimulate	1	Familiarization
	Rest	1	Preparation for test
	Test 1	1-2*	Obtain data
	Rest	5	Combat fatigue
	Stimulate	10	Learning
	Rest	1	Preparation for test
	Test 2	1-2	Obtain data

* Usually a fixed number of letters, namely 80, was included in the test. Thus, when the letter rate was increased in later experiments, the test duration decreased.

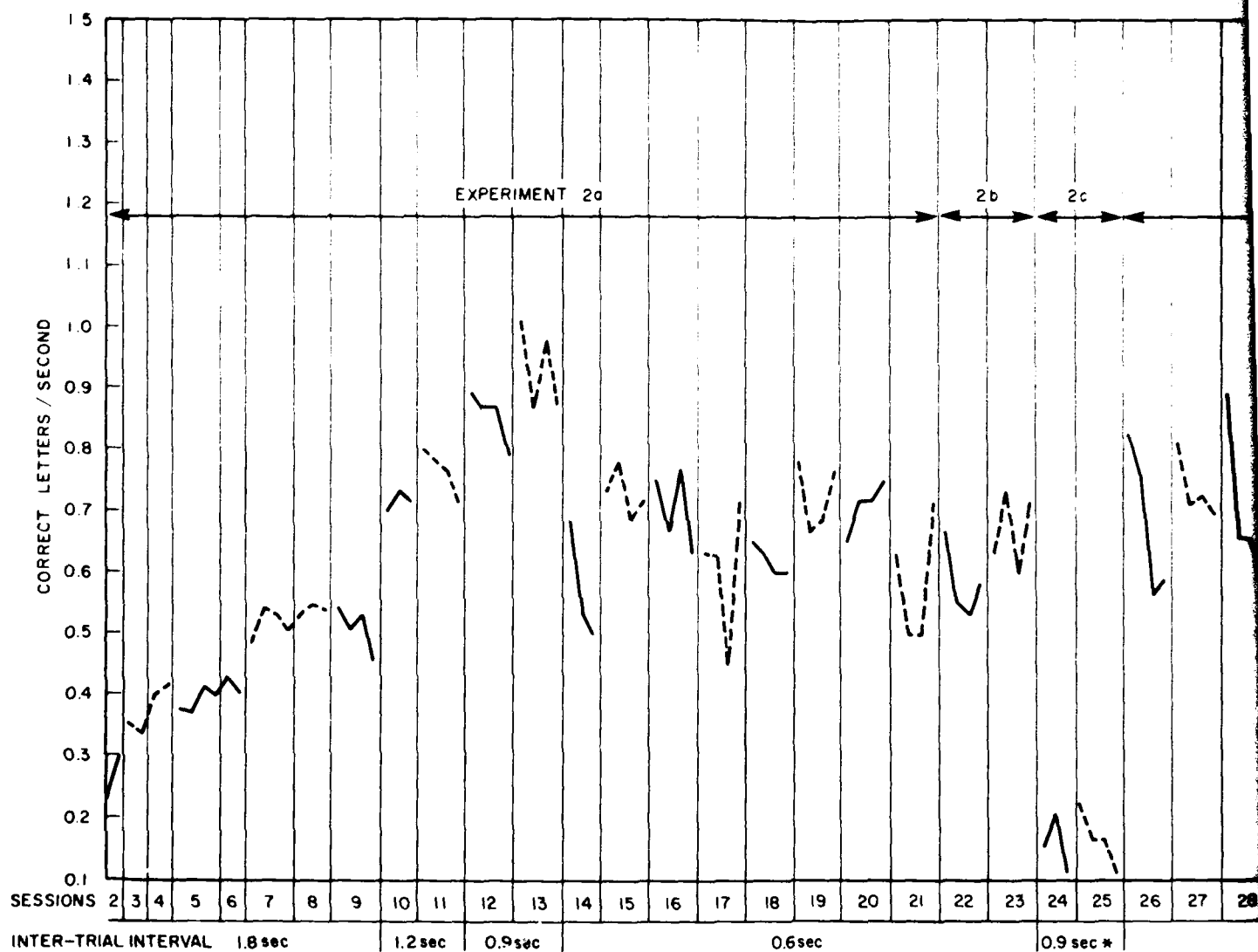
The short rest immediately preceding each test enabled the subject to prepare for the test. The number of tests permitted the observation of learning and/or fatigue over the course of the hour. Since the first test (No. 1) in any session occurred at the beginning of the session (after only one minute of familiarization) and the last test (No. 4) occurred at the end of the session, a comparison of Test 1 in Session N with Test 4 in Session (N-1) yielded a measure of performance difference, with no intervening learning. The possibility of complication due to intervening recovery from fatigue was alleviated by comparing the hour's average of the four tests in Session N with that of the four tests of Session N-1. But again, this measure was complicated by the possibility that different amounts of learning might have occurred within two consecutive sessions, in which case the measure might be more an indication that more learning occurred in Session N than in Session N-1 rather than that performance was better with the mode of stimulation used in Session N than with the mode used in Session N-1. However, this in itself is interesting, and furthermore, the two measures ("first and last tests" and "averages") together do give a fairly good picture of the effects of the intersession variable (motion vs no-motion).

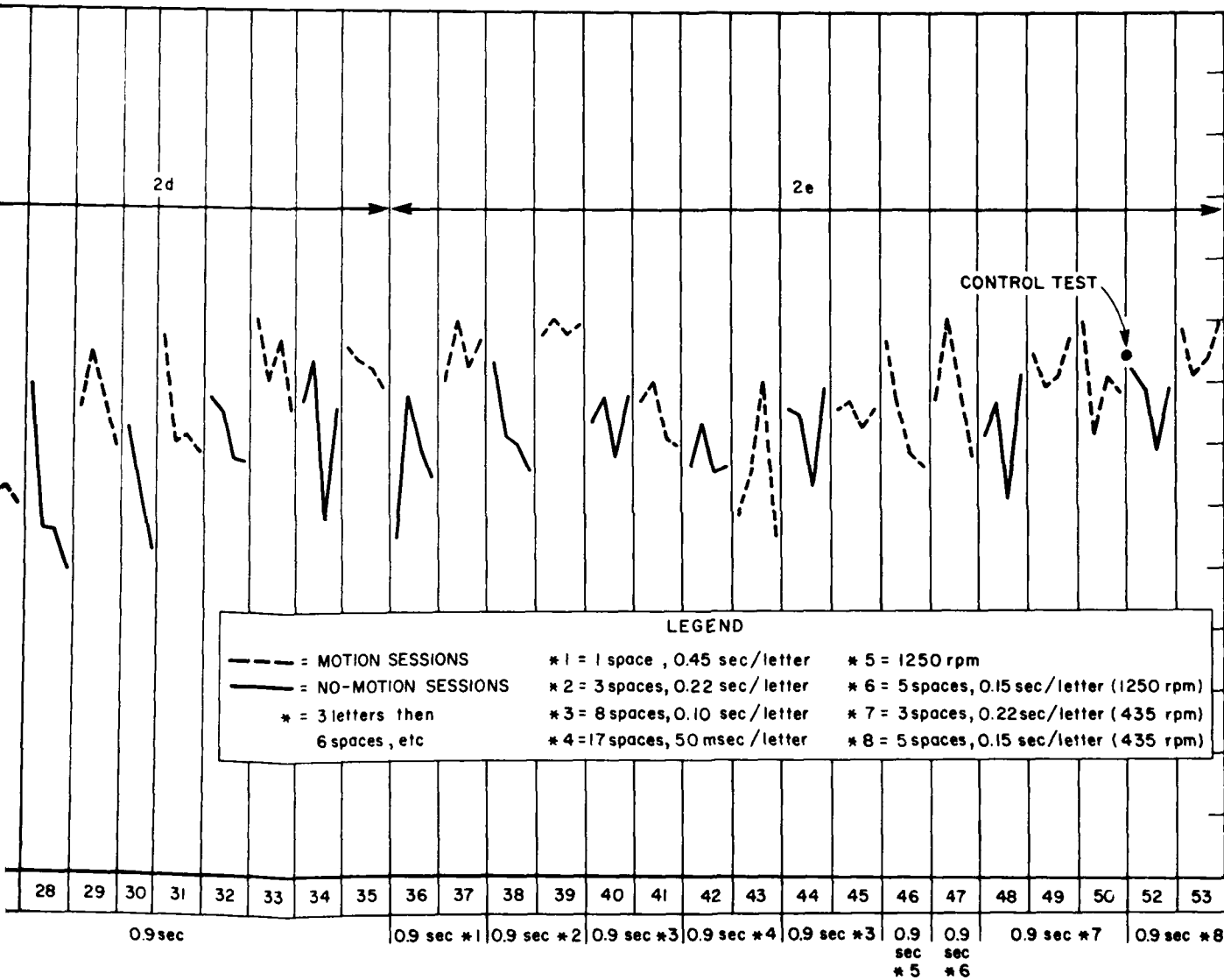
In some cases the computer was unavailable for completion of all four tests within a session, but in no case were fewer than two tests completed per session. With the above exception, all of the sessions with Subject 9 were run according to the protocol shown in Table VI-2.

The results of Sessions 2 through 13 constitute a learning curve during which rotation and no-rotation sessions were alternated. After Session 2, the sessions were alternated according to the following sequence: rotation, rotation, no rotation, no rotation, rotation, rotation, and so on. The effect of this double alternation was to counterbalance any possible morning vs afternoon effects on the subject's performance, since two sessions were run per day. The results of this experiment are shown in Figs. VI-1 and VI-2, Sessions 2 through 13. Figure VI-1 gives the individual test scores and Fig. VI-2 shows the average for each session. Here we see that when going from a motion to a no-motion trial (Sessions 4 to 5, 8 to 9, and 11 to 12*) the subject's performance decreased or remained constant (using as measures both the comparison of the last and first tests and the comparison of session averages), and that when going from no-motion to motion (Sessions 2 to 3, 6 to 7, 10 to 11, and 12 to 13) the subject's performance increased (again, according to both measures). These results lead to the conclusion that the type of rotation of the stimulus array used here may be effective in increasing performance during the learning of tactual reading of a symbolic letter alphabet.

A simple sign test of whether performance increased, decreased, or remained constant when the modes of stimulation changed yielded a tentative significance level beyond 0.01. This result is strengthened by the fact that in the three cases where double alternation was used with no change in the stimulus (e.g., going from a motion to a motion, or a no-motion to a no-motion session), performance always increased. This makes the finding that performance decreased (or, in one case remained constant) when going from motion to no motion all the more significant, since the decrease was evident even though it was imposed on a learning curve which should have tended to conceal it.

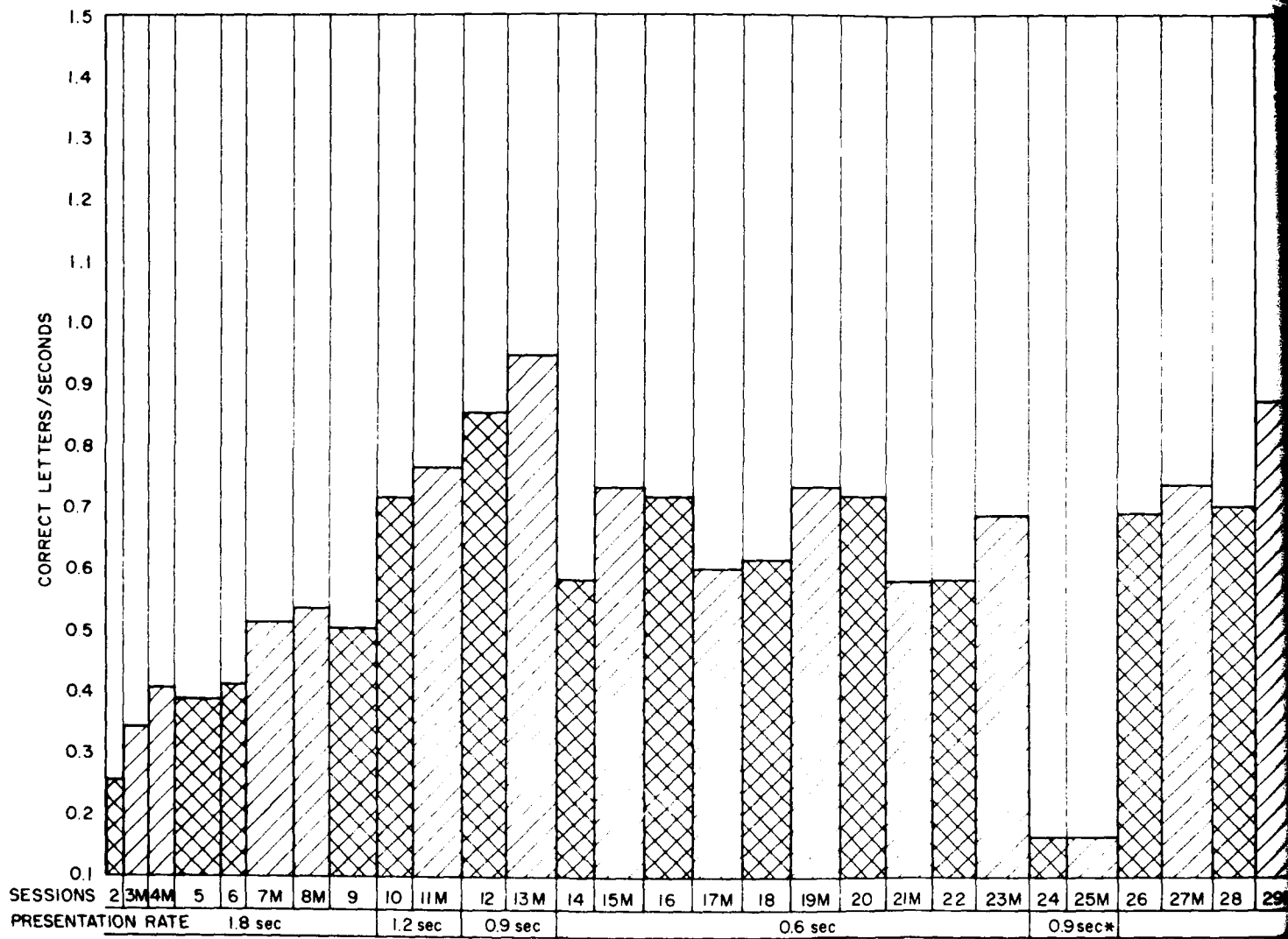
* In going from Sessions 11 to 12, the accuracy decreased, even though the number of correct letters per second increased, due to the reduction in inter-trial interval.

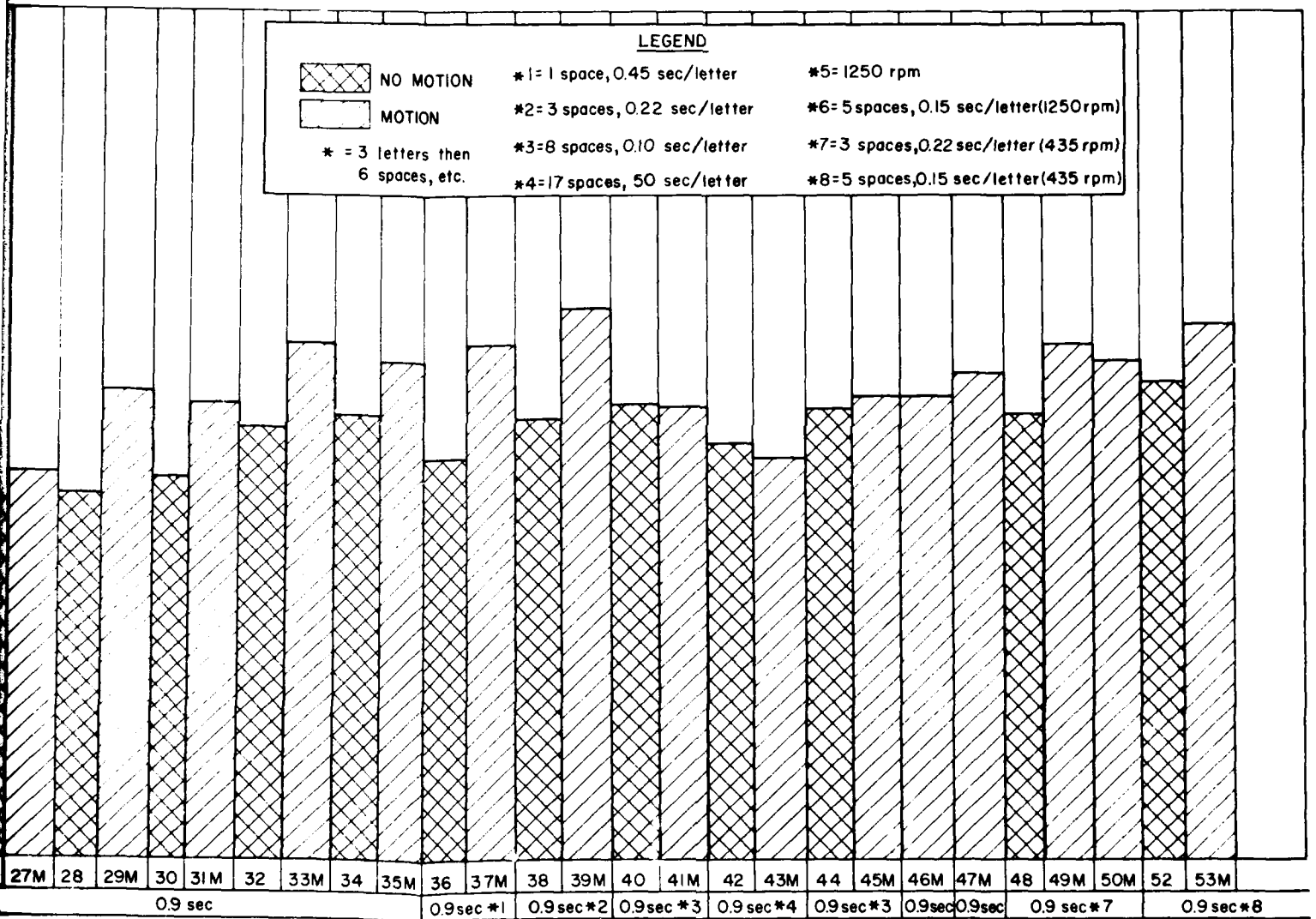




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FIG. VI-1 TEST SCORES FOR EACH SESSION





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FIG. VI-2 AVERAGE OF TEST SCORES FOR EACH SESSION

After Session 13, another space was dropped from between each letter. The presentation was therefore letter, space, letter, space, etc., at an average rate of 0.6 seconds per letter. This presentation was maintained from Session 14 through Session 21 (Fig. VI-1 and -2). It was found that (1) the subject's performance (both percent correct and letters per second) decreased, and (2) the previously noted difference between motion and no motion completely disappeared. Thus, while the average percent correct before Session 14, at 0.9 to 1.8 seconds per letter, was 86.1 percent for all motion sessions and 76.6 percent for all no-motion sessions, at 0.6 seconds per letter (Sessions 14 through 21), the average for all motion sessions was 39.7 percent correct, and for all no-motion sessions, 39.5 percent correct.

Thus, the fast letter rate completely obliterated the motion/no-motion difference previously found. The hypothesis was then made that the reason for this variation was that at the faster rate, the subject's great difficulty in responding rapidly enough became the limiting factor in his performance, and that the sensory aspects of reading the letter become relatively unimportant. The evidence for the response difficulty was simply (1) that the subject missed long strings of letters (as if once he became unsure of a letter he fell behind and was lost for a while); (2) that he often failed to respond at all (which had not happened before, even in the beginning of his learning); and (3) that he often became tongue-tied, slurring or mispronouncing letters.

Attempts were then made to correct this hypothesized bias towards response difficulties.

b. Sessions 22-23

The first attempt consisted of the same letter, space, letter, presentation but allowed the subject to stop and start the presentation at will. The results are shown in Figs. VI-1 and VI-2, Sessions 22 and 23. Here we see that while some improvement was obtained with motion, it was (if real) small. During these two hours the subject did not improve his performance at all over the previous 0.6-sec/letter sessions. Part of the reason for this lack of improvement may have been that the

subject did not stop the presentation more than five or six times per test, and therefore may not have been able to exercise his privilege to the best effect.

c. Sessions 24-25

The second attempt to circumvent the hypothesized response difficulty involved a slowdown to an average 0.9 seconds per letter and a change in the configuration of the presentation. The subject was now presented with three random letters in a row, followed by six spaces. Thus, in the first 0.9 seconds he received three random letters; in the next 1.8 seconds he was allowed to name the letters; and then he received three more letters, six more spaces, and so on. The results of this experiment are shown in Figs. VI-1 and VI-2, Sessions 24 and 25. Under these conditions, the performance was extremely poor. The fact that the subject missed almost every middle letter of the triads suggests that some type of masking was in part responsible for the poor performance. While the middle letter miss rate was lower with motion than without, the overall performance did not differ, and we must conclude that motion made no appreciable difference in the subject's ability to perform. One additional finding in these two triad sessions was that by considering a response correct when it was out of proper sequence but in the proper triad, the subject's performance in both sessions (after correcting for guessing) was doubled. Thus, by counting KJP in response to PJA as two letters correct (the P and J) instead of one (the J) the subject's accuracy (corrected for guessing) increased from 11 percent to 20 percent.* This is in agreement with the results reported by Kolers and Katzman (1963) for a visual experiment in which the subject was asked to name sequentially-presented English letters. At letter rates approximately only twice as fast as the ones used in the tactual experiments described herein, and in letter groups of three, it was found that letter reversal was a common phenomenon. This similar finding, for both touch and vision, supports the hypothesis that part of the problem in the triad experiment was, if not a response difficulty, at least at a higher level than the immediate sensory one; i.e., the letters were getting in but were jumbled. That hypothesis does not adequately account for the fact that in Sessions 22

* For similar results in memorization, see M. Mitchell, "Errors in the Memorization of Numbers," Am. J. Psych., XLV, January 1933.

and 23 (self-control of presentation), the subject did no better than in previous sessions at 0.6 seconds per letter, and that in Sessions 24 and 25, even when out-of-sequence responses were counted as correct, the accuracy was very poor. This is especially evident when Sessions 23 and 24 are compared with previous Sessions 12 and 13 and subsequent Sessions 26 through 35, where the same letter rate (0.9 seconds per letters) was used without grouping the letters.

In the letter, space, letter, space sessions, the accuracy and correct letter rate is about four times as great as that in the triad experiment. Thus, a masking effect must be chiefly to blame when the letters are run together (presented with no intervening empty frames.)

d. Sessions 26-35

After Session 25, because the subject had been responding for so long (eleven sessions) at a relatively low level, and because the motion/no-motion difference in performance had been lost, an attempt was made to measure any loss of ability that had taken place and to ascertain whether or not the motion/no-motion difference had been artifactual.

Thus, the conditions in effect in Sessions 13 and 14 just prior to the drop in performance (namely, 0.9 second per letter) were reinstated, since these conditions yielded the highest correct-letter rate. The results are shown in Figs. VI-1 and VI-2, Sessions 26-35. It is obvious that while performance had been adversely affected by the intervening eleven "bad" sessions, the motion/no-motion difference was again apparent and reliable, and the subject again began to improve his performance. It was tentatively concluded that the effects of motion under fairly widely varying conditions of performance, presentation rate, and state of learning increase the accuracy with which a subject can read a tactually presented symbolic letter alphabet, but that these beneficial effects can be obliterated under certain types of letter masking and response difficulties.

e. Sessions 36-53*

These sessions were run to determine further under what stimulus conditions movement (jitter) of the stimulus apparatus improved the performance of the subject. It was found that the motion/no-motion difference was statistically significant, that performance increased with stimulus presentation time, but that forced response confounded the results. (Because of this last effect, Experiment 3 was run, in which the subject's response triggered the next stimulus.)

By this time the subject was highly practiced in making verbal responses to a briefly presented stimulus. In each trial in these sessions, a letter was presented to the subject, and 900 msec after the onset of the stimulus, a new stimulus was presented.

Two factors were investigated: (1) motion versus no motion of the stimulating apparatus, and (2) variation of the total revolutions per presentation by variation of the presentation time (the rotation frequency for each session is shown in Fig. VI-1 along with the performance scores). Thus, the fixed response time required the subject to respond faster when stimulus presentation time was increased. However, during any one experimental session, presentation time as well as the number of revolutions per presentation were held constant. Each session consisted of four test runs of approximately 90 trials each. The data were analyzed according to a two-way analysis of variance; the results of this analysis are shown in Table VI-3.

The results for the experimental sessions were analyzed according to the equation

$$y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_{ij} + e_{ijk} \quad (\text{VI-1})$$

where

i = 1, 2 indices for no motion and motion (factor I)

j = 1, ..., 6 indices for revolution/letter (factor J)

* This experiment was designed and reported on by S. Link.

Table VI-3
ANALYSIS OF VARIANCE FOR SESSIONS 36-53

Source	Sums of Squares	df	Mean Square	Level of Significance
Motion vs No Motion	78.65	1	78.65	$\alpha < 0.005$
Revolutions per letter	96.35	5	19.27	$\alpha = 0.010$
Interaction	73.25	5	14.65	$\alpha < 0.050$
Error	187.28	36	5.20	
Total	435.53	47		

y_{ijk} = number of correct responses for test k in session (i,j)
 μ = overall mean
 α_i = effect due to factor I
 β_j = effect due to factor J
 γ_{ij} = effect due to interaction of I and J
 e_{ijk} = error in measurement.

Considering the order of magnitude of the interactions (Table VI-3), we cannot conclude that $\gamma_{ij} = 0$. Hence, the response may not be strictly linear in factors I and J (that is, the response is not additive in the treatment effects). However, it may be safely concluded that averaged over revolutions per letter, there is a significant ($\alpha < 0.005$) difference between the motion versus no-motion methods of stimulus presentation. Motion leads to a marked increase in the number of correct responses by the subject.

The interpretation of factor J is somewhat more obscure. First, large computed estimates of the linear and cubic components of the variance suggest that there may be a nonlinear transformation of the responses capable of reducing the interactions.

However, it should be noticed that each session consists of a different response time, confounded by changes in the number of revolutions per letter of the airjet array. Consequently, although we can conclude ($\alpha = 0.01$) that there are significant differences among the six sessions, the differences exist only when the sessions are averaged over all variations in revolutions per letter and presentation times.

To investigate the effect of forced response, several additional experimental sessions were run. Averaging the dependent variable y given by

$$y = 0.023 + (\text{correct letters per sec with motion}) \\ - (\text{correct letters per sec without motion})$$

resulted in the data shown in Fig. VI-3.

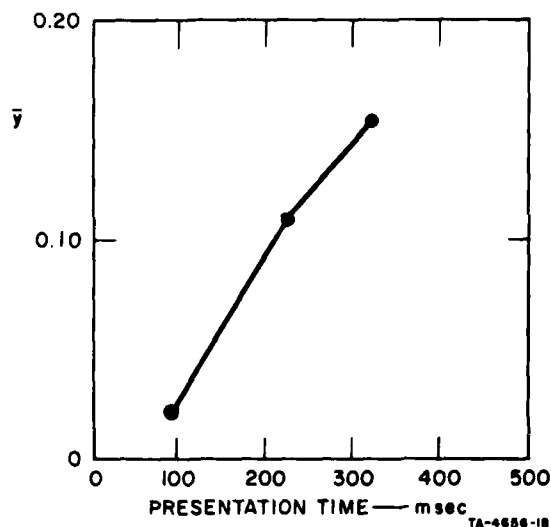


FIG. VI-3 EFFECT OF STIMULUS PRESENTATION TIME ON PERFORMANCE

For the range of values examined it appeared that the response was linear with presentation time, although performance increased at a decreasing rate owing to the subject's being forced to respond during a shorter interval of time.

Finally, an analysis of the frequency of occurrence of error-error pairs on successive trials during a session was run to substantiate the hypothesis that forced response resulted in a greater number of errors, owing to the decrease in response times. It was found that error-error pairs increased with presentation time and hence, increased with reduced response time.

In summary, Sessions 36 through 53 indicated:

- (1) Motion (versus no motion) results in a substantial increase in number of correct responses.
- (2) The response was essentially a linearly increasing function of presentation time over the range of values examined.
- (3) Forced response introduced unnecessary error into the experiment.

These results suggested more careful control of the presentation factors as well as free response by the subject. Moreover, it suggested that optimum response was directly related to presentation time and revolutions per letter of the frame motion apparatus and could be profitably explored to gain further insight into the perceptual mechanism.

3. Experiment 3--Effect of Stimulus Pattern rpm and Stimulus Duration Time*

From the previous experiment it was concluded that a subject presented with a coded alphabet closely resembling the shapes of letters in the English alphabet performed substantially better when the presentation apparatus was made to translate along a circular locus. In order to examine more carefully the influence of stimulus presentation time and revolutions of the airjet frame, a complete quantitative factorial experiment was designed.

Two subjects, S9 from the previous study and a new, untrained subject (S10) were used. Subject 10 was given five 1-hour sessions of training before beginning the experiment. The subject's task was to identify letters presented tactually by the airjets of the frame motion

* This experiment was designed and reported on by S. Link.

apparatus. Although the stimulus was carefully controlled, in this experiment the subject was not forced to respond during a fixed length of time. Each subject made a verbal response, after which he operated a foot switch, which allowed the computer to proceed with the next stimulus presentation. Each experimental session consisted of a control test followed by three tests under a new experimental condition. During both control and experimental tests, subjects were presented the alphabet three times (i.e., a total of 78 letters) in a random order. Subjects were given an arm and hand rest to facilitate relatively constant stimulation of the same area of the hand.

Two factors, consisting of four levels of presentation time and five levels of rpm, were replicated by each subject. Factor I, presentation time, consisted of levels 100, 200, 300, and 400 msec, while factor J, rpm, consisted of levels 0, 200, 400, 800, and 1200. At the beginning of each control session a test was run at 400 msec and 800 rpm.

The results for S9, the subject in the previous experiment, are reported in Table VI-4. Since the control variable contained little variation, it was not included in the analysis. Figs. VI-4 and VI-5 show the performance versus the amount of treatment. The variability of the means is indicated by the dispersion of cell means about a column mean. Again, the analysis of variance results from the equation

$$y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_{ij} + e_{ijk} \quad (\text{VI-2})$$

and is shown in Table VI-5.

Casual examination of the analysis indicates that the response is linear with stimulus presentation time. In fact, computation of these treatment effects, assuming only linearity, results in the data presented in Table VI-6, where

$$\hat{\alpha}_i = y_{i..} - y_{...}$$

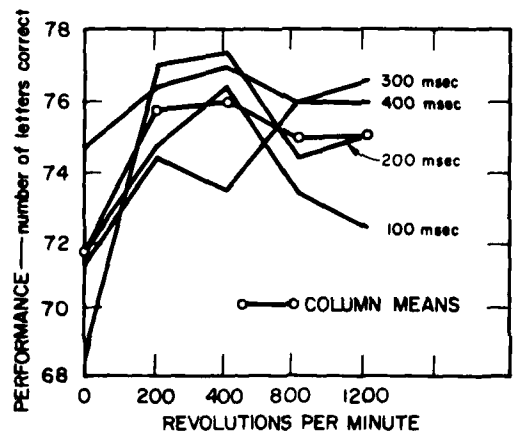
(period indicates an average over the index occurring in that position)

and $\hat{\alpha}_i^*$ = an estimate of $\hat{\alpha}_i$ based solely on the linear regression coefficient.

Table VI-4

DATA FROM STIMULUS MOVEMENT EXPERIMENT 3 FOR S9
 [ENTRIES ARE MEANS OF NUMBER CORRECT (OUT OF A POSSIBLE 78)
 FROM THREE TESTS]

Factor I (msec)	Factor J (rpm)					Row Means	Treatment Effects (α_i)
	0	200	400	800	1200		
100	71.7	74.7	76.3	73.3	72.3	73.667	-1.05
200	68.7	77.0	77.3	74.3	75.0	74.466	-0.25
300	72.3	75.3	73.3	76.0	76.7	74.733	0.02
400	74.6	76.3	77.0	76.0	76.0	76.000	1.28
Column Means	71.833	75.833	76.000	74.916	75.000	74.716 = overall means	
Treatment Effects (β_j)	-2.883	1.117	1.284	0.200	0.284		



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FIG. VI-4 PERFORMANCE AS A FUNCTION OF RPM

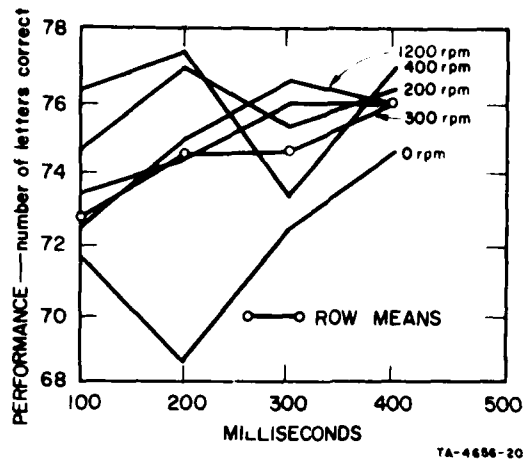


FIG. VI-5 PERFORMANCE AS A FUNCTION OF STIMULUS PRESENTATION TIME

Table VI-5
ANALYSIS OF VARIANCE FOR EXPERIMENT 3

Source	df	Sums of Squares	Mean Square	Level of Significance
Rows	3	(42.183)	14.061	$\alpha < 0.001$
linear	1	39.603		
quadratic	1	0.817		
cubic +	1	1.763		
Columns	4	(135.933)	33.983	$\alpha < 0.001$
linear	1	35.208		
quadratic	1	70.720		
cubic	1	30.000		
remainder	1	0.005		
Interaction	12	100.733	8.394	$\alpha < 0.001$
Error	40	91.333	2.283	
Total	59	370.183		

Table VI-6
TREATMENT EFFECTS

msec	α_1	α_1^*
100	-1.05	-1.09
200	-0.25	-0.36
300	0.02	0.28
400	1.28	1.09

Needless to say, except for exceedingly small variability, linearity is obtained in this experiment as well as in the previous experiment.

Although the factor for rpm can be subjected to similar analysis, it seems apparent that a third-degree equation will describe the average response to increasing revolutions.

Similarly, careful analysis of interaction components might reveal another source of variation in the response. However, examination of the control variable indicates that most of the interaction can be removed without affecting the results for treatment effects.

In summary, S9's response for the range of variables explored can be described by an equation of the form

$$y_{ij} = \mu + \alpha_i + \beta_j \quad (\text{VI-3})$$

where

μ = an overall mean level of performance, characteristic of the subject and the experimental treatments

$\alpha_i = kt$, where k is a constant and t is stimulus presentation time

$\beta_j = c_1b + c_2b^2 + c_3b^3$, where c_1 , c_2 , and c_3 are constants and b is the rpm.

Further analysis of the data can provide additional insight into the functioning of the perceptual mechanism. More specifically, one could provide an exact account of the operation of the mechanism under the

range of conditions explored. One problem invariably faced in experiments of this sort is variation of the perceptual mechanism versus variation of the particular subject. An analysis of the data from one subject affords no distinction between these different sources of variation. For this reason a second subject participated under identical treatment conditions.

The data for S10 were considerably more variable than those for S9. These data are reported in Table VI-7 along with the values of the control variate and the randomization scheme for assigning treatments. Although

Table VI-7
DATA FROM STIMULUS MOVEMENT EXPERIMENT 3 FOR S10

Factor I (msec)	0	Factor J (rpm)				α_1
		200	400	800	1200	
	7	2	20	1	9	
100	74 70.3	68 61.3	73 75.0	62 64.6	75 72.3	-0.597
	4	10	17	14	15	
200	73 67.3	77 73.6	76 77.6	76 77.0	77 76.6	-0.129
	6	19	3	12	16	
300	75 74.6	71 74.6	71 70	77 75.3	77 75.6	0.018
	18	13	5	8	11	
400	76 72.3	77 77.3	75 76.6	75 75.6	75 73.6	0.707
β_j	-2.488	-1.525	1.983	2.214	-0.182	

Per each cell:

Numbers appearing in upper right hand corner are session numbers.

Decimal entries are cell means for test scores.

Integer entries are values of the control variate.

an analysis of covariance fails to support the hypothesis of linearity, examination of the randomization scheme versus the control variable indicates that for S10, considerable improvement in performance occurred in the control variable up to Session 10. Hence, the lack of linearity may be a failure of the subject to discriminate accurately in the mid-range of the time variable during learning. Since similar effects confound

the analysis of rpm, further analysis of these data seem premature. At present, S10 is being retrained to a high criterion of performance on the control variable. Subsequently, he will replicate the initial experimental sessions.

4. Experiment 4--Effect of Amplitude of Stimulus Pattern Movement

In the previous experiment it was found that for S9, the optimum setting of vibration frequency, for an amplitude setting of 0.8 cm, was about 400 rpm. It was also found that performance increased linearly with duration of stimulus over the range 100 to 400 milliseconds. In this experiment we wished to evaluate the effect of amplitude variation. The results we will see indicate that amplitudes in the range 0.4 to 0.8 cm for 400 rpm, and 0.4 to 2.5 cm for 200 rpm are about optimum.

In order to lower the percent accuracies below those of the previous experiment and to reduce the effects of previous training, it was decided to run this test using the block letter alphabet discussed in Section II, Fig. II-4, rather than the specially designed alphabet used in the previous experiment. As we noted earlier, the block letter alphabet is more difficult than the specially designed alphabet. In fact, the latter was designed precisely because of difficulty with the block letters.

Subject 9 was given two hours training on the block letter alphabet, which he had never felt before. Then he was given a series of tests with different amplitude settings. Four tests were run for each amplitude setting. The sequence of amplitude settings was chosen as the experiment progressed. In Fig. VI-6 are plotted the results for each setting, the spread in results for the four tests, and the average. The numbers next to the plotted points indicate the sequence of these tests. The sequence is significant because the subject was not very well trained before starting the experiments, and therefore we might expect some learning during the sequence. The relatively small extent of this learning can be seen from the slightly increased performance between the first and last experiment for the same conditions, namely 0.8 cm and 400 rpm.

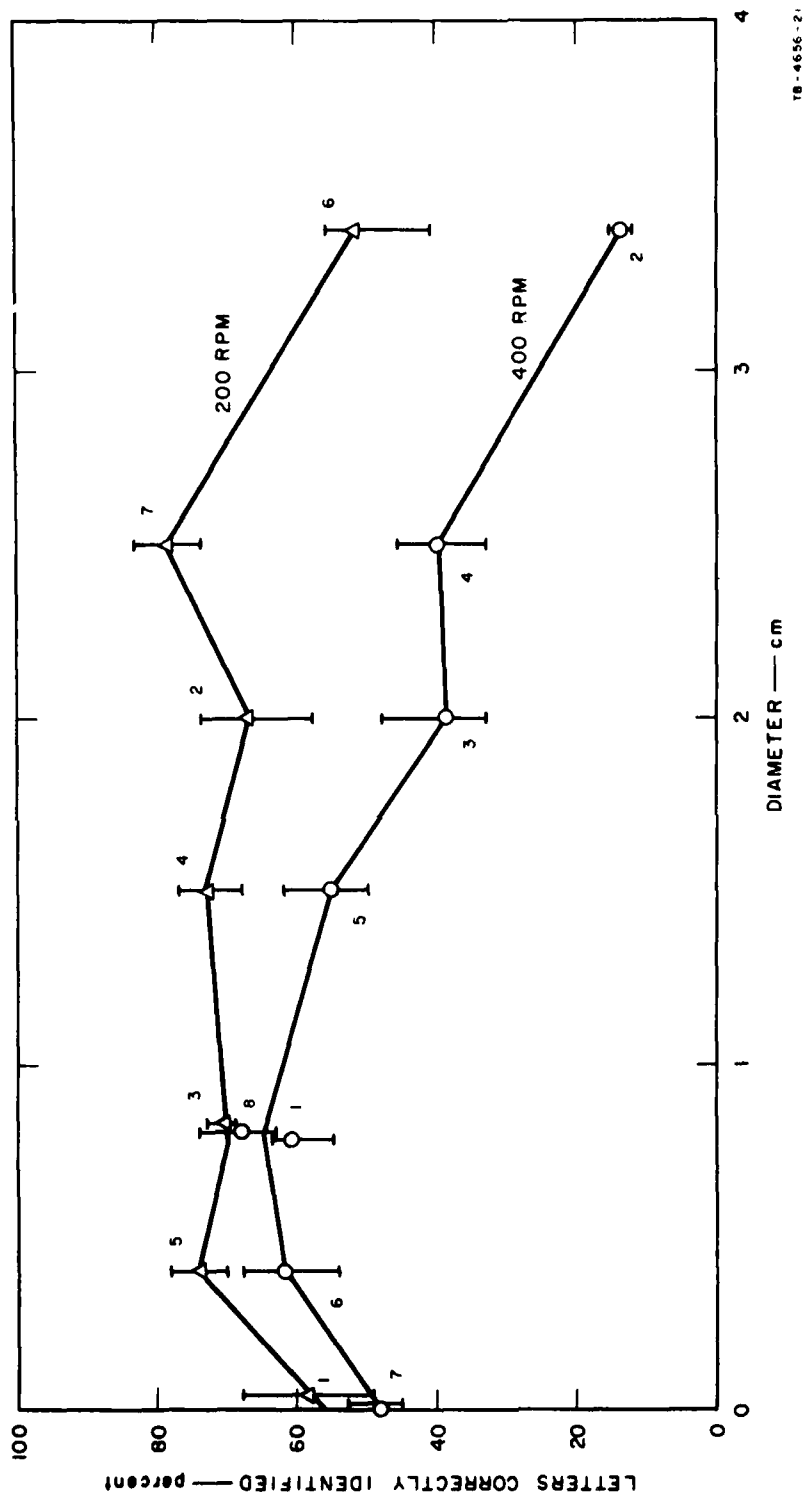


FIG. VI-6 EFFECT OF AMPLITUDE OF CIRCULAR TRANSLATION OF STIMULUS ARRAY ON RECOGNITION OF BLOCK LETTERS

5. Discussion

From the results thus far, it is clear that rotational vibration of the type described here improves performance. From Table VI-1, which resulted from the first exploratory experiment, one gets the impression that the "best" sensation occurs for a certain linear velocity of display movement. Although these results are very rough it is quite clear that the best frequency of vibration decreases monotonically as the amplitude increases. As a tentative hypothesis, then, let us assume that the best performance is obtained for a certain linear velocity of display. From the results of the third and fourth experiments regarding the effects of vibration frequency and amplitude, we can obtain an estimate of what this velocity might be. A peak in performance for S9 was obtained for an amplitude of about 0.8 cm, a display rotation frequency of 400 rpm (or 150 msec per revolution), and a jet frequency of 200 pulses per second (or a pulse every 5 msec). Thus, the pattern is repeated every $150/5 = 30$ times during each revolution, or every 12 degrees of rotation. With a path diameter of 0.8 cm, this frequency leads to a velocity along the circular locus of about 15 cm/sec, which corresponds to what would be obtained with the Times Square programs and the bimorph array operating at 67 words per minute.

Additional experiments will be conducted to help formulate hypotheses of what this velocity might correlate with, or to determine whether this tentative hypothesis is even valid. It will be especially interesting if the spatial and temporal results from these experiments can somehow be connected with the sensory sampling times from tracking experiments.

The finding that performance is a linear function of stimulus presentation time over the range 100 to 400 msec agrees roughly with that reported by Bliss and Massa (1961) for a kinesthetic-tactile experiment and a visual experiment. Bliss and Massa found that while performance in a kinesthetic-tactile task was logarithmic with stimulus presentation time over the range of 10 to 500 msec, visual performance in the analogous experiment reached a minimum at about 60 msec.

C. Estimation of Stimulus Position and Physical Length of Stimulus Pattern

In coding an analog parameter into a tactile display, for example an error signal in tracking experiments, one needs to know what techniques lead to the best performance. Therefore, some experiments were designed to investigate the effects of number of stimulators, time delays, and anatomical position on the ability of the subjects to distinguish eight stimuli representing eight different lengths or magnitudes. These experiments were especially planned to aid in the development of tracking displays such as those described in Appendices F and G.

These experiments were exploratory; only two to four subjects were used in each case. The subjects were male with college education and ranged in age from 20 to 36. Minimal training was given, perhaps five minutes before each experiment. Thus, these experiments indicate only initial performance for a wide range of stimulus conditions. This approach was taken primarily in an attempt to get some indication of which stimulus conditions warranted further study.

1. Experimental Arrangement

The computer programs used were the Experimental Performance and Line-Scan routines described in Appendix E. Masking noise was used in all experiments to mask auditory cues. (An initial run without masking noise gave roughly 0.3 bits more transmitted information per stimulus than the same experiment with masking noise.) The subject was in a separate room from the computer and experimenter. Each stimulator operated from an independent oscillator, and all the oscillators vibrated in the range 70 to 100 cps. The air pressure into Airjet Stimulator Array1 was 10 psi.

2. Procedure

The letters "a" through "h" were used to designate the eight stimuli as described later in this section. The experimenter presented each stimulus by typing one of the letters "a" through "h" on the on-line typewriter. The subject responded orally with the number (1 through 8) which he thought corresponded to the stimulus, and the experimenter typed this response. Thus, a typed record of each experiment was obtained.

For training, the experimenter presented the stimulus sequence designated by a - h twice. Then 30 or 40 stimuli were presented in a random sequence. The subject attempted to identify each of these stimuli and was told immediately if he was wrong. After this training, the experiment was begun, during which the subject was not told whether he was right or wrong. In each experiment, 10 presentations were made of each stimulus in random order, so that a total of 80 stimuli were presented.

The stimulus location in the experiments was either the right index finger or the forehead. The stimuli to the finger were collinear along the ventral side of the finger. For the forehead, the stimuli were horizontally collinear in the mid-forehead.

The responses from each experiment were transformed into a confusion matrix. From these matrices, information measures were calculated according to the following formulae given by Attneave (1959):

$\hat{H}(x)$ = estimate of average information in each stimulus

$$= \log n - \frac{1}{n} \sum_i n_i \log n_i$$

$\hat{H}(y)$ = estimate of average information in each response

$$= \log n - \frac{1}{n} \sum_j n_j \log n_j$$

$\hat{H}(x,y)$ = estimate of average information in each stimulus-response pair

$$= \log n - \frac{1}{n} \sum_{i,j} n_{ij} \log n_{ij}$$

$\hat{T}(x,y)$ = estimate of the average transmitted information
or the average amount of information each response
gives about the stimulus

$$= \hat{H}(x) + \hat{H}(y) - \hat{H}(x,y)$$

where

- n = the total number of stimulus presentations
 n_i = the number of times the i^{th} stimulus was presented
 n_j = the number of times the j^{th} response was received
 n_{ij} = the number of times the i^{th} stimulus was presented and the j^{th} response was received.

3. Experimental Results

Nine different sets of experimental conditions were tried. Seven of these were tried on both the right index finger and the forehead. Table VI-8 gives the transmitted information for each experiment, Table VI-9 compares the finger experiments with the forehead experiments, and Table VI-10 compares the performance obtained for the various stimulus conditions. The experimental conditions for each experiment and comments relative to each experiment are given below.

Table VI-8
TRANSMITTED INFORMATION
No. of Stimuli = 8 Stimulus Entropy = 3 bits
Stimulus Spacing = 1/4 in. L = 1, 2, 3, ..., 8

Experiment No.	No. of Stimulators Activated	Anatomical Position	Stimulus Duration (msec)	Time Delay (msec)	Stimulus Sequences	Transmitted Information (bits)				
						Subject				
						S14	S15	S2	Average S14 + S2	Average S14 + S15 + S2
1	1	Finger	200	--	--	2.03	2.12	1.94	2.03	2.03
	1	Forehead	200	--	--	2.20	1.61	1.91	1.91	
2	2	Finger	100L	100(L-1)	Ref. last	2.03	2.23	2.06	2.17	2.12
	2	Forehead	100L	100(L-1)	Ref. last	2.23	2.06	2.15	2.15	
3	2	Finger	50L	50(L-1)	Ref. last	1.68	2.01	2.16	2.09	1.95
4	2	Finger	200	100	Ref. first	1.51	1.75	1.85	1.80	1.70
	2	Forehead	200	100	Ref. first	1.61	1.51	1.42	1.47	
5	2	Finger	200	100	Ref. last	1.44	1.68	1.77	1.73	1.63
	2	Forehead	200	100	Ref. last	1.44	1.52	1.68	1.60	
6	2	Finger	200	0	--	1.55	1.84	1.68	1.76	1.69
	2	Forehead	200	0	--	1.45	1.79	1.87	1.83	
7	2	Finger	200	100	Repeated	1.47	1.48	2.01	1.75	1.65
8	3	Finger	200	0	--	0.86	1.66	1.30	1.48	1.27
	3	Forehead	200	0	--	1.43	1.13	1.28	1.28	
9	L + 1	Finger	200	0		1.42	1.86	1.63	1.75	1.64
	L + 1	Forehead	200	0		1.76	1.76	1.76	1.76	

Table VI-9
COMPARISON OF TWO LOCATIONS FOR TACTILE STIMULATION
Stimulus Spacing = 1/4 in.
Stimulus Entropy = 3 bits
Subjects: S15 and S2

Transmitted Information

Experiment Number	1	2	3	4	5	6	7	8	9
Finger	2.03	2.17	--	1.80	1.73	1.76	--	1.48	1.75
Forehead	1.91	2.15	--	1.47	1.60	1.83	--	1.28	1.76

Table VI-10
COMPARISON OF PERFORMANCE FOR VARIOUS STIMULUS CONDITIONS
Anatomical Position: Finger
Subjects: S2, S14, S15

Experiment Number	Description	Average Transmitted Information
2	2 points 100 (L-1) msec delay	2.12
1	1 point	2.03
3	2 points 50 (L-1) msec delay	1.95
4	2 points 100-msec delay Ref. first	1.70
6	2 points Simultaneous	1.69
7	2 points Repeated	1.65
9	2 points Simultaneous	1.64
5	2 points 100-msec delay Ref. last	1.63
8	3 points Simultaneous	1.27

EXPERIMENTAL CONDITIONS

COMMENTS

Experiment 1	One of eight collinear stimulators were turned on for 200 msec. The stimulators were spaced 1/4 inch on centers.	The relatively high performance from presenting only one point at a time indicates absolute position is probably the most important stimulus aspect in all of these experiments. Examination of the errors obtained from this experiment indicate that the stimulator spacing was approximately equal to the error of localization on the finger and the forehead.
Experiment 2	Two stimulators were turned on in time sequence. The first stimulator was one of the eight used in Experiment 1. The second stimulator turned on was always a ninth or reference stimulator located at the proximal end of the finger or the right side of the forehead. The time delay between the stimulators was proportional to the distance between them according to the relation, time delay in msec equals $100(L-1)$, where L is an integer from 1 to 8 indicating the distance between the stimulators. Thus there was zero time delay between the activation of the stimulators for a "1" stimulus.	The stimuli in this experiment had two redundant cues, space and time. The time cue added significantly to the transmitted information (compare with Experiment 5). Apparent motion was felt with Stimulus 2 (time delay of 100 msec) but not with Stimuli 3-8.
Experiment 3	This experiment was the same as 2 except the time delay between the stimulators was only half as long.	Apparent motion was felt for Stimuli 2 and 3 but not for Stimuli 4-8.
Experiment 4	In this experiment two stimulators were activated always with a 100 msec time delay. The first stimulator activated was always the reference at the proximal end of the finger or the right side of the forehead. The second stimulator activated was one of eight equally spaced stimulators along a line.	Apparent motion was felt for all stimuli in this experiment. The subjects reported that the apparent motion was stronger on the finger than the forehead. It was felt that presentation of the reference stimulator first was better than last since it seemed to warn or set the subject so that attention could be focused on the data stimulator.
Experiment 5	This experiment is the same as 4 except that the reference stimulator was presented last instead of first.	In this experiment on the finger the reference stimulator seemed to mask perception of the data stimulator.
Experiment 6	In this experiment, two stimulators were activated simultaneously. One of the two, the reference, was always the same.	Simultaneous presentation of the two stimulators seemed to mask the perception of the data bearing stimulator. Apparent position was noticed on Stimuli 1 and 2 but not on 3 to 8.
Experiment 7	This experiment is the same as 6 except that the stimulus was repeated once parallel to and 1/4 inch from the first presentation.	Repetition of the stimulus seemed to mask rather than aid the perception.
Experiment 8	In this experiment three stimulators were activated simultaneously. The outside stimulators were always the same and served as a reference. The middle stimulator was one of eight equally spaced collinear stimulators.	In this experiment it was initially thought that presentation of the end points would improve the performance since the position of the middle stimulator relative to the outside stimulators could be estimated. Thus, a reference length instead of a reference position was given the subject. However, from the reduction in performance, it is evident that the reference stimulators tended to mask the middle stimulator whose position was judged on the basis of anatomy. In fact, it was difficult to distinguish between Stimulus 1 and Stimulus 8.
Experiment 9	In this experiment a "full line" was presented by activating simultaneously $L + 1$ stimulators, where L is one of the integers (1) through (8). These stimulators were equally spaced and collinear.	There were two redundant cues in this experiment, location of the stimulators and intensity, of stimulation. Comparing the results with Experiment 6, the intensity of stimulation cue did not increase the performance.

4. Discussion

Results described by Attneave (page 72) from visual and auditory experiments have shown "... that the information conveyed by stimuli varying on a single dimension is likely to fall somewhere between 2 and 3 bits, and that increasing the number of alternative stimuli beyond the minimum mathematically necessary to transmit this limited amount of information results in little or no improvement of transmission." These results are from experiments to determine the amount of information transmitted in absolute judgment of the pitch of pure tones or the position of a pointer along a linear scale. We see from Table VI-1 that the best transmission rate obtained in our experiments was better than two bits per second, which is in the same range. Falling at the low end of the 2- to 3-bit range might be due to the fact that the spacing of the stimuli in these experiments, which was limited by the physical size of the array, was comparable to the error of localization.

But a second point regarding redundancy must be noted. Eriksen (Attneave, page 75) found a transmission of 4.1 bits for stimuli varying in size, brightness, and hue (compared with an average of 2.7 for bits for these attributes employed separately), even though the three attributes were perfectly correlated with one another, so that any change in one always involved a concomitant change in each of the other two. Comparing experiments 1 and 2 in Table VI-8, we see that redundancy (in this case, stimulus duration) only added about 0.1 bits of transmitted information, implying that stimulus duration is not an effective information-bearing parameter in this experiment.

Some other observations are:

- (1) It is easier for subjects to identify different lengths (coded into stimulus patterns) by estimating the positions of a stimulator relative to parts of the anatomy than by estimating the distance between two stimulators simultaneously activated or activated with a fixed delay.
- (2) If two stimulators are activated with a fixed time delay between them, one stimulator representing a spatial reference and the other representing a distance to that reference, then better performance results when the reference stimulator is activated first.

- (3) For airjet stimulation, the average error of localization on the finger is about 1/4 inch.
- (4) For a fixed stimulator spacing of 1/4 inch, the finger is slightly better than the forehead.

These experiments were run quite early in the program. With the increased insight gained since then, and with the vastly improved capability for running experiments, there would seem to be an advantage from rerunning certain similar experiments. For example, it would be interesting to examine the effect of stimulus pattern "jitter" on transmitted information. Any quantitative results regarding spatial and temporal effects from this type of experiment, in combination with results from "jitter" experiments and tracking experiments, would be of the utmost importance in developing models for tactile perception.

D. Signal Detection Theory Approach to Two-Point Discrimination*

The specific goals of this portion of the study were:

- (1) To determine the relation between d' (a measure of the observer's ability to distinguish between a pair of stimuli) and the distance between the two stimuli.
- (2) To obtain receiver operating characteristics (ROC curve), which, in this case, is a plot of the observers probability of saying that two stimuli are different when they did in fact impinge upon two different loci versus his probability of saying that they were different when they occurred at the same point.
- (3) To determine if a model consistent with the theory of ideal observers and with no restrictive assumptions could be used to predict the absolute locations (not solely the shape) of the ROC curves on the basis of ABX data. (The ABX experiment is described in Section D-1-a.)

In the first case, it was hypothesized that a simple linear relation would exist between d' and the distance between two stimuli. Because of the additive nature of d' , such a relationship would have strong predictive potential. In the second case, it was hypothesized that the shapes of these

* This experiment was designed, carried out, and reported by F. Clarke.

ROC curves would be consistent with those found in audition. Such a result would suggest that much of the theory of signal detection could be applied to the study of tactual perception and would demonstrate the importance of taking into account of the observer's criterion or bias in measuring his ability to distinguish among tactual inputs. Because of the basic importance of the ROC curve, it was obtained by two different procedures, a rating procedure and a binary choice method. It was hypothesized that both methods would result in the same ROC curve.

1. Procedure

A single observer, S16, was used throughout these feasibility studies. The site of stimulation was the inner side of the forearm, approximately midway between the wrist and elbow. Stimulation was provided by a nearly identical pair of airjet stimulators (described in Appendix B) located 3/8 inch from the surface of the skin. A single stimulus presentation consisted of a train of eleven pulses with 10 msec between onsets. The noise produced by the stimulators was masked by a low-frequency "grey" noise presented to the observer over earphones.

a. ABX Experiment

Performance on an ABX task was studied as a function of distance between stimulators. Five values of separation were used: 0.15, 0.90, 1.65, 2.40, and 3.15 cm. The two stimulators were arbitrarily labeled A and B. On any given trial, one of the two was randomly chosen and activated; then the second stimulator was activated, and was followed by either A or B (again randomly chosen). The task of the observer was to give a response indicating whether the final stimulus was more similar to the first or second stimulus preceding it. The time from onset to onset of stimuli within a given trial was 900 msec. A given trial (stimulator A, followed by stimulator B, followed by stimulator X, followed by the observer's response) took 5.4 seconds. Trials were run in blocks of 50 followed by a rest period. Experimental conditions were changed after every block with appropriate counterbalancing for possible order effects. Prior to the recording of experimental data, the observer had approximately 29 hours of practice at this task. This rather excessive practice time

was necessitated by our difficulties in finding a highly reliable pair of matched stimulators. Experimental data consist of 500 observations at each of the five distances between stimulators.

b. "Same-Different" Experiment--Binary Choice

In this experiment, the distance between the two stimulators was held constant at 1.65 cm. A trial consisted of one of the following four orders of presentation: AB, AA, BA, or BB. On any given trial the order was chosen randomly. The task of the observer was to respond either that the two stimulations were by the same stimulator or by different stimulators. Because there were only two stimuli per trial, the trial interval was shortened to approximately 4.5 seconds. The experimental variable was the instruction under which the observer operated. On some blocks of trials he was instructed to respond "same" only if he was very sure that the stimuli did indeed arise from the same stimulator; otherwise he was to respond "different." On other blocks of trials he was instructed to respond "different" only if he were very sure that this was the correct response, and otherwise to respond "same." Under a third set of instructions he was told to give his best guess as to whether or not the two stimuli were generated by the same stimulator. After one and a half hours practice on this task, data were recorded. The data obtained consisted of 750 observations per data point, with conditions counter-balanced to avoid systematic error owing to order effects.

c. "Same-Different" Experiment--Rating Scale

Stimuli were presented as in the binary-choice experiment above. The observer's task was to respond "one" if he was very sure that the stimuli were generated by the same stimulator, "two" if he thought this was the case but was not sure, "three" if he thought different stimulators were involved but was not sure, and "four" if he was very sure that different stimulators were used. Receiving operating characteristic ROC curves for three different distances between stimulators (0.90, 1.65 and 2.40 cm) were obtained. Data collection proceeded following three hours of practice on this task. The data consisted of 750 observations per condition, with appropriate counter-balancing for order effects.

2. Results

The measure d' is a performance measure based on the assumption that sensory stimuli give rise to a normally distributed decision variable. (For an elementary discussion of signal detection theory see Clarke, 1963.) Where two stimuli differ in value on a single physical dimension, it is assumed that each gives rise to a normally distributed random value, each with a different mean value. The measure d' is the separation between the means when the distributions are scaled for unit variance. In an ABX experiment, it is assumed that the stimulation A gives rise to a random variable x_1 , B to x_2 , and X to x_3 . If $|x_1 - x_3| \leq |x_2 - x_3|$, then the observer will respond "A"; otherwise he will respond "B". In the latter case, the relation between proportions of correct responses and d' is given by the following equation (Pierce, 1958):

$$P(c) = 0.5 + \frac{1}{\pi} \int_0^{d'/\sqrt{6}} e^{-x^2/2} dx \cdot \int_0^{d'/\sqrt{2}} e^{-x^2/2} dx$$

where $P(c)$ is the proportion of correct responses.

Using this equation to convert proportion of correct responses to d' and plotting d' as a function of separation between the two stimulators, we obtain the relationship shown in Fig. VI-7. There are 500 observations per data point. The bars through the data points indicate the standard error of the mean. The straight line is a visual fit through the origin, where d' must be zero if the stimulators are identical. This line is a fairly good fit to the data with the exception of the point at 0.15 cm. Figure VI-8 shows the same data plotted with percent correct as the dependent variable. The solid curve is that obtained when the values of d' given by the straight line in Fig. VI-7 are converted back to percent correct by the above equation. With the exception of the point at 0.15 cm, the theoretical curve fits the data quite well. This point represents the closest separation possible between the two stimulators and was obtained as a check on whether or not the stimulators might differ in some unknown way which the observer might detect. The location of this point suggests that this is a possibility, though a deviation of 3 percent from chance

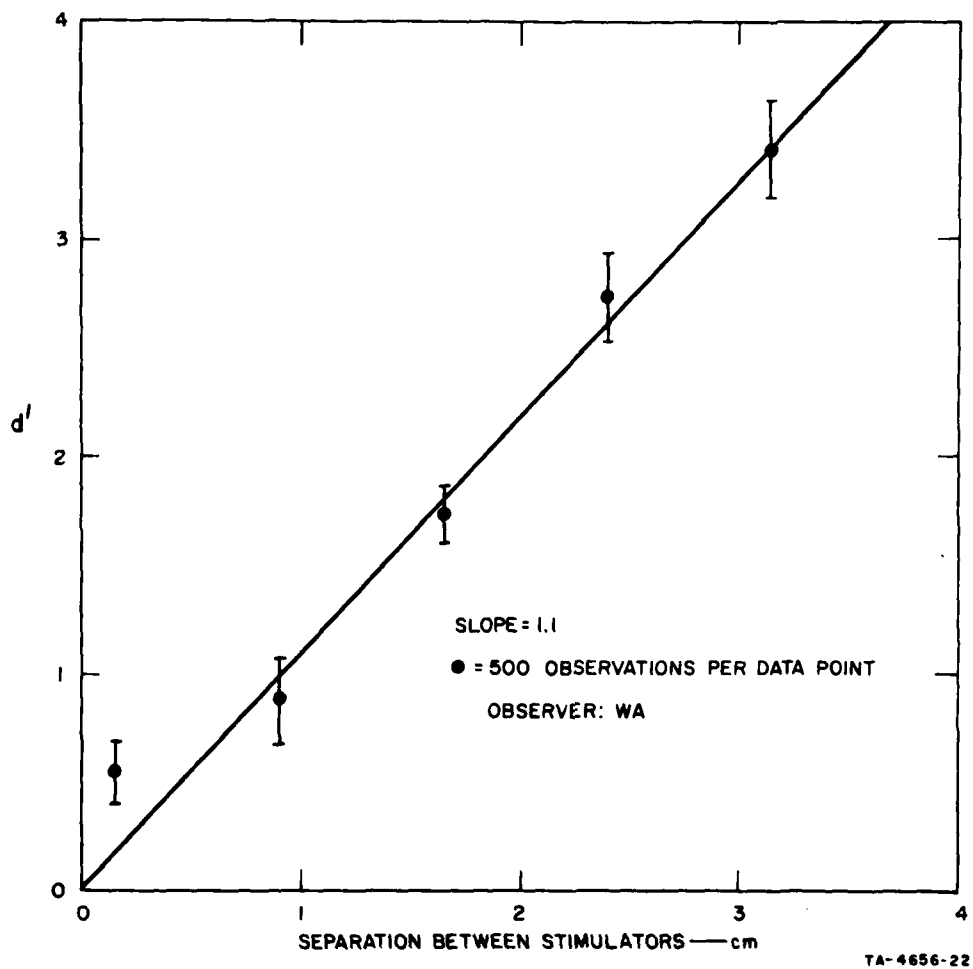


FIG. VI-7 d' VS SEPARATION BETWEEN STIMULATORS
FOR THE ABX EXPERIMENT

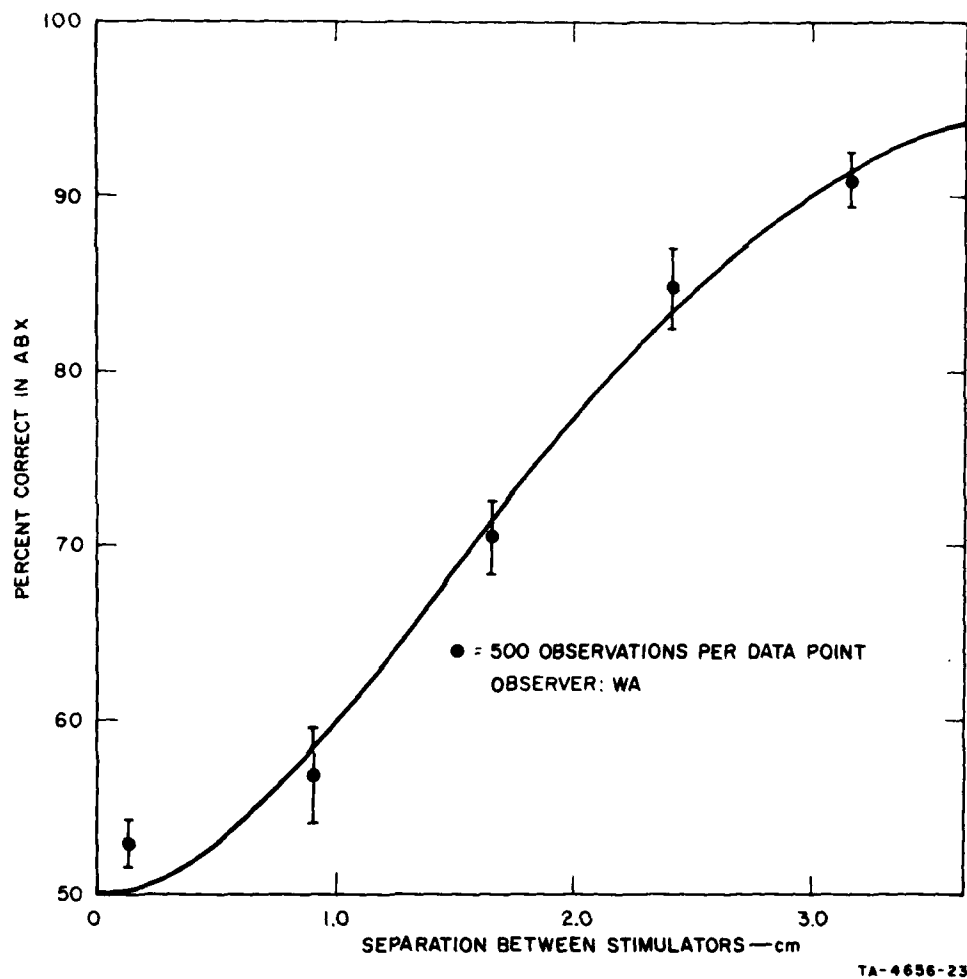


FIG. VI-8 PERCENT CORRECT VS SEPARATION BETWEEN STIMULATORS FOR ABX EXPERIMENT

performance cannot be taken too seriously on the basis of these data. We conclude that these data are consistent with the hypothesis that d' is linear with separation between stimulators. But, as we shall see, the data obtained in the third experiment offer conflicting evidence.

The open circles in Fig. VI-9 show the relation between the observer's "hit rate" and "false-alarm rate" as instructions are varied in the "same-different" binary-choice experiment. Here, hit rate is defined as the observer's probability of responding "different" when the stimuli were

in fact generated by different stimulators. The false-alarm rate is defined as the observer's probability of responding "different" when the stimuli were generated by the same stimulators. The points are ordered logically, i.e., the point with the lowest hit rate and lowest false-alarm rate was obtained when the observer was instructed to be very sure the stimuli were generated by different stimulators before responding "different". The middle point was obtained when he was instructed to make his best guess, and the highest when he was to be sure the same stimulator was responsible for both stimuli.

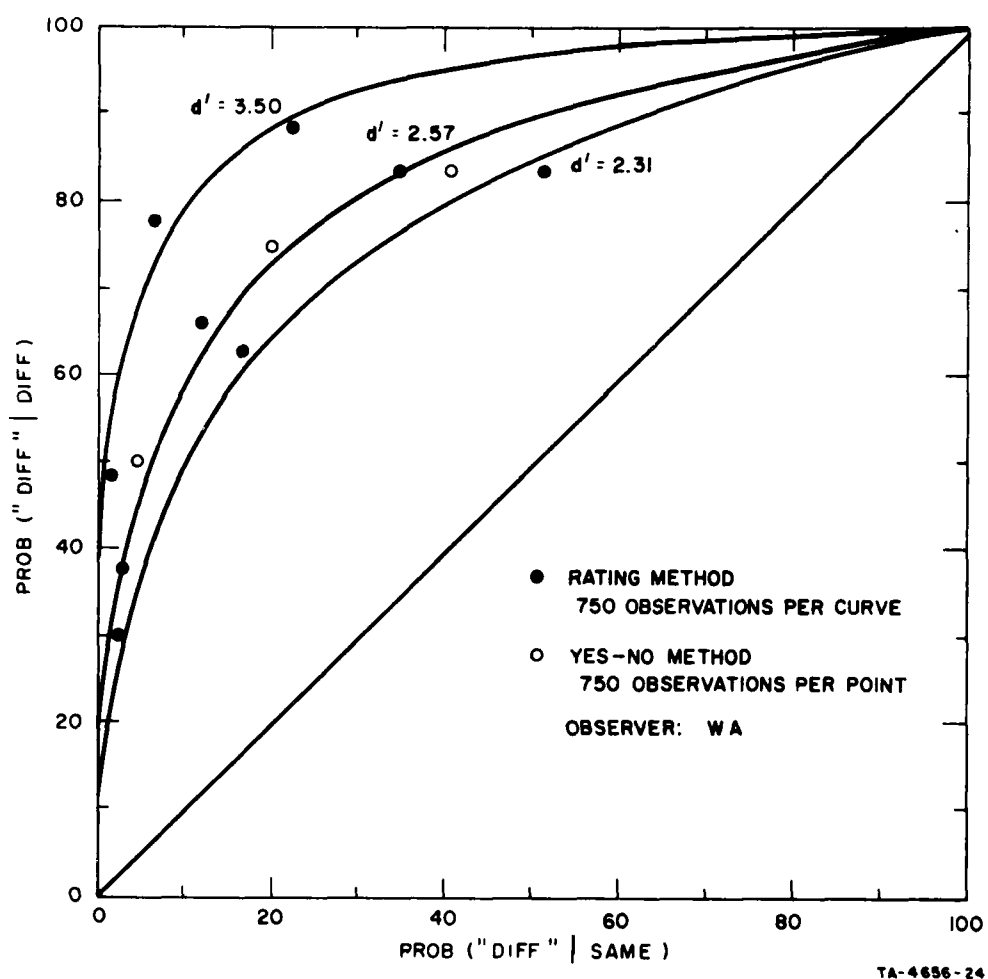


FIG. VI-9 ROC CURVES

The solid points in Fig. VI-9 were obtained in the "same-different" rating experiment. For each of the three curves, the lowest point represents the probability that the observer would respond "four" when the stimulators employed were different [$P(4|D)$] plotted against his probability of responding "four" when the stimulators employed were the same [$P(4|S)$]. The next highest point on each curve represents $P(4 \text{ or } 3|D)$ versus $P(4 \text{ or } 3|S)$, and the highest is a plot of $P(4 \text{ or } 3 \text{ or } 2|D)$ against $P(4 \text{ or } 3 \text{ or } 2|S)$. The open circles and solid points for the middle curve appear to define the same function, and we feel relatively safe in concluding that both methods give rise to the same ROC curve. For more information on these two methods of generating ROC curves see Egan, Schulman, and Greenberg, "Operating Characteristics Determined by Binary Decisions and by Ratings" in Swets, 1964.

The solid curves passing near the points are of the shape one would obtain in a "same-different" experiment if the observer's performance was consistent with the hypothesis that the sensory stimulation gave rise to a normally distributed decision variable.* There is some suggestion that the data points break slightly more sharply than the theoretical curves, but it is clear that a d' measure would give a much more constant measure of the observer's ability to distinguish between the two hypotheses than would a hit rate corrected for "guessing," as commonly employed in psychophysics. We feel that the theory of signal detection provides relatively good predictions of the shape of the obtained ROC curves.

The curves of Fig. VI-9 are labeled with the values of d' which were used to generate them. It will be noted that these values are quite different from those obtained in the ABX experiment. This means that the very simple model which we had hoped to use to relate the two types of experiments is inadequate. It would appear that the observer is better able to handle the simpler decision process required in the "same-different"

* See Sorkin, R. D., "Extension of the Theory of Signal Detectability to Matching Procedures in Psychoacoustics" in Swets, 1964.

experiment than he is the more complex process required in the ABX experiment, or that long-term memories are involved in the decision process. It may also be noted that the values of d' obtained in this "same-different" experiment are not linear with the separation between the stimulators. Consequently, we must regard the results in the ABX experiment, for the time at least, as specific to that technique and not generalize on the basis of those data without further study of the problem.

3. Discussion

The results of these experiments must be treated cautiously. The experiments are purely exploratory studies with but a single experimental subject. However, the following summary statements appear warranted:

- (1) We are not in a position to conclude that d' grows as a linear function of spatial separation between loci of stimulation, although the results in the ABX experiment suggest that this possibility should not be rejected without further experimentation.
- (2) We feel relatively safe in concluding that the theory of signal detection does a fairly good job of predicting the shape of the ROC curve. Furthermore, we feel it very likely that both methods of obtaining ROC curves will give essentially the same results in studies of tactual perception. These conclusions are bolstered by knowledge of similar findings in audition and vision.
- (3) Definition of the relationship between data obtained in the ABX experiment and the "same-different" experiment is pending a more complex set of assumptions than we feel justified in making at this time.

VII OVERALL PLANS AND DISCUSSION

Each section of this report contains a subsection titled "Discussion," treating results and their relation to the work discussed in other sections of the report. In this section we have attempted to give an overall view of our plans for the project and the significance of tactile research in general.

Recent engineering interest in the potential applications of tactile communication systems has increased the need for broad studies in tactile perception. Potential clinical uses for the tactile tests that could evolve from such studies, e.g., tactile tracking tests, are also of interest. Tactile studies are, therefore, important in their own right; however, they may be very useful for comparative purposes as well. The development of engineering models for any one of the three major sensory "systems," audition, vision, and taction, may be significantly helped by results from studies in either of the other two. There is little question that comparable data rates can be achieved in all three systems. In particular, the tactile system seems to have a number of the attributes of both the visual and auditory systems. Von Békésy, for instance, has shown that considerable psychophysical similarities exist between audition and taction, and we have already seen how readily the familiar visual alphabets can be perceived tactually.

Some interesting psychophysical experiments have led to speculation on a short-term visual memory of 0.25 to 1.0 seconds that may be important in "chunking" the continuous stream of visual input (see Massa, 1964). Techniques for erasing this short-term memory and interfering with its readout have been demonstrated. One is led to wonder whether there is an analogous short-term tactile memory. If so, how do its properties compare with those of vision? Is there an erase function? It is interesting that the saccadic eye-movement rate falls in the same range as that of the short-term visual memory (Gaardner, *et al.*, 1964). If saccadic movements are important in the operation of the visual short-term memory, is there a tactile equivalent of saccadic movement? It may

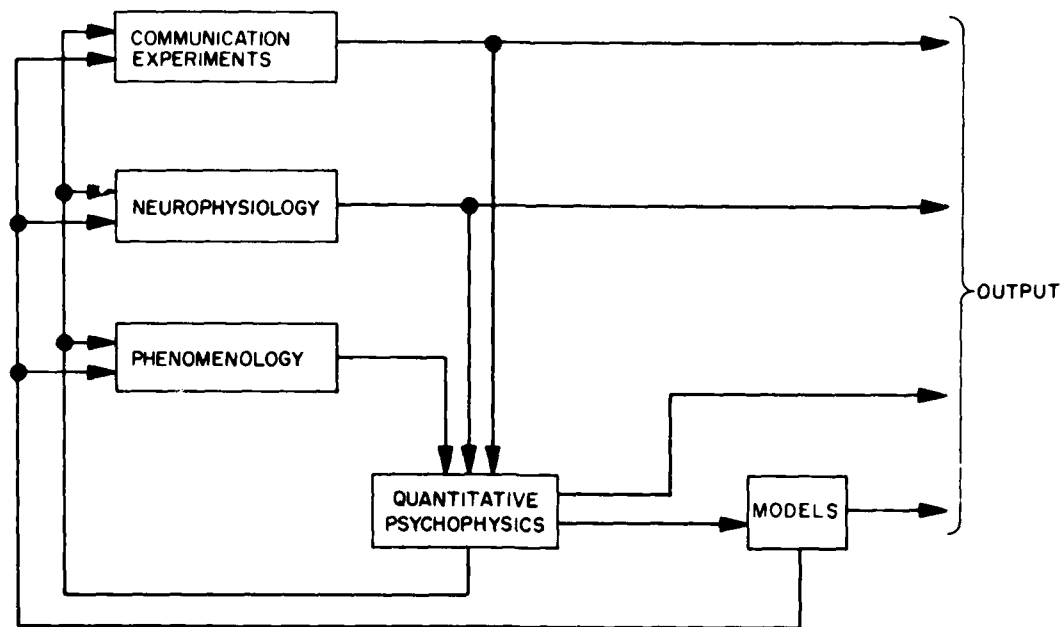
well be that tactile experiments on short-term memory might help clarify the modeling even of the visual system.

In taction there are the familiar "modes" or descriptive terms of hot, cold, touch, pressure, itch, tickle, pain, smooth, rough, and so on. As discussed in the introduction to this report, there is considerable controversy over the nature of the tactile receptor endings, in particular the number of different types. There may be an interesting parallel here to color vision, for which we imagine three relatively distinct types of receptors that together provide a great range of color perception. Land (1964) in his "retinex theory" has provided an interesting model to describe the manner in which the outputs from these three retinal "sheets" may be combined to explain a number of the facts of color perception. Are there a number of basic tactile "sheets" that similarly combine to provide the wide range of tactile perception? Are there elements of a common model for color vision and taction?

We tend to consider the visual and auditory systems as relatively independent; however, there can be important interactions. Shipley (1964), for example, reports that when visual flashes and auditory clicks are presented simultaneously, the reported visual flash rate can be drastically affected, and in fact driven, by simultaneous auditory clicks, which occur at a different frequency. However, the perceived auditory click rate is substantially unaffected by the simultaneous visual flashes. This experiment shows an interesting asymmetric relation between these two systems. Expanded experiments involving simultaneous tactile "clicks" might be helpful in determining the interrelationship of these systems.

The work discussed in this report, plus future work, can be organized according to the pattern shown in Fig. VII-1. There are four main "outputs" from this type of program: (1) models, as they develop; (2) results of individual quantitative studies; (3) results of data transmission experiments, like those of the tactile-tracking and tactile-language studies; and (4) results from neurophysiological studies.

The study of data transmission techniques may lead to the development of useful engineering systems for display and control purposes or for helping sensorily handicapped individuals. These studies will also



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FIG. VII-1 OVERALL PROGRAM SCHEMATIC

lead to the formulation of quantitative psychophysical experiments (e.g., the pattern vibration experiments discussed in Section VI), the results of which can be important in the system design. The results of quantitative and neurophysiological studies and the data from models as they evolve will not only be interesting in their own right but, as discussed above, will be important for comparative purposes as well. The facility for flexible control of complex temporal-spatial stimuli should significantly affect the nature of physiological studies as it affects visual perception studies (see Hubel and Weisel, 1962).

It has often been demonstrated that qualitative, subjective, phenomenological studies by themselves can be dangerous and misleading. For this reason we do not consider them as direct program "outputs," although the material of Section V is of this nature. However, as discussed in the introduction, the performance of a large number of relatively brief experiments, not even necessarily well controlled, seem important for guiding the selection of the necessarily small number of quantitative studies that can be performed. We expect there will be

considerably more experiments of this type, especially as we enlarge the physical range of our stimulation. Thus far, the total stimulus pattern has been limited to a rectangle of a couple of inches on a side. Study of the transmission capability of our entire tactual sheet of a dozen or so square feet will require stimulation over more extensive areas.

We tend to think of the retina as a relatively uniform screen, with a central foveal region of greater resolution, to be sure, but otherwise relatively uniform. In particular, we do not think of specialized points on the retina as special landmarks. Tactually, however, we have learned a great many specialized anatomical positions that we can point to accurately with little difficulty, even with our eyes closed. What effect do these landmarks have on coding possibilities? Consider a visual experiment in which a single spot of light is flashed tachistoscopically, and the subject is simply asked to record its two-dimensional position. This is an experiment involving two physical dimensions (an x and a y coordinate), and it is typically found that about 4.4 bits per presentation is achieved (Attneave, 1959, page 72), which is equivalent to an absolute definition of $2^{4.4} \approx 20$ two-dimensional locations. Tactually, however, we can do considerably better. We can readily identify several dozen tactile locations with substantially 100-percent accuracy. We have conducted preliminary experiments with a "typewriter" code, in which a typewriter keyboard is coded onto the array of ten fingers with three rows of stimulators, one for each of the three regions between the joints of each finger, and with two positions for each such region of the index fingers, defining 30 positions all told. These experiments have demonstrated that 100-percent correct identification can be achieved at slow rates. In the development of tactile codes, this achievement leads to the question, how important is anatomical position relative to spatial relationship? In other words, we know we can transmit language via a code involving complex letter shapes, say, in the form of English letters, in which the structure of the letter is the important factor and the absolute anatomical position is immaterial, as long as the stimulus location has adequate resolution. On the other hand, we also know that we can devise codes in which each letter is specified by unstructured stimulation of a unique anatomical position. Is there an optimum

mixture of relative shape and absolute position for highest data rates? We might consider the effective dimensionality of our two-dimensional tactual skin surface, including the effects of learned anatomical position. Attneave (1959, page 74) reports an average increase of 1.7 bits per presentation for each doubling of dimensionality. Thus, for example, for a four-dimensional experiment we could expect $2^{4 \cdot 4 + 1.7} \approx 60$ absolute identifications.

In a different vein, there are also important questions regarding the interaction of material simultaneously presented at different spatial locations. Can we effectively pay attention to just one at a time? Is there a tactile "cocktail party" effect?

We see then that there are many interesting questions to ask. With a number of relatively brief phenomenological experiments we hope to be able to identify a relatively small number of quantitative experiments to perform. These, it seems, will provide important data for developing overall models, i.e., an understanding of tactile performance.

Apart from direct transmission, there are other interesting studies to pursue. For example, we noted the sensation of three-dimensional apparent motion effects in connection with Fig. V-6. Though these effects were achieved only over relatively small physical distances, we might inquire whether the same effects can also be achieved over wider areas of the body. In fact, most of the phenomenological experiments of Section V, which were performed, so to speak, "in the small," in the sense of stimulation over a small area, can be extended to larger areas. Apart from data transmission capability, it may well be that the tactual system has sensory function unmatched by, or at least different from, the auditory and visual systems, which may indeed make the "feelies" of Mead (1954) a reality.

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Appendix A
AIRJET ARRAY 1

Appendix A*

AIRJET ARRAY 1

The first version of an electromagnetic valve suitable for construction in a relatively large array is shown in Fig. A-1. The air pressure in the box acts as a return force, together with the metal spring, to seal the valve. When the coil is energized, the iron slug is pulled into the gap, thereby opening the valve. Because of the low inertia of the slug, and the short stroke, these valves can operate at frequencies up to 200 cps. A simple and inexpensive relaxation oscillator circuit built to drive this valve in the desired frequency range is shown in Fig. A-2.

For a 2-psi air pressure pulse measured 1/8 inch directly above the airjet outlet, the pressure waveform has a rise and fall time of about a millisecond and a width of about 3 milliseconds. The pressure waveform is shown in Fig. A-3. For an oscillation frequency of 80 cps, therefore, air flows only about 25 percent of the time. Subjects report that the sensation with this duty cycle is actually more localized than with a 50-percent duty cycle. If the region of skin being stimulated is examined under stroboscopic light, traveling waves can be seen at least an inch away from the stimulation point. However these waves are not sensed as such. [Similar results have been reported by von Békésy (1955, 1958).]

In the 12-by-8 array, the stimulators are 5/8 inch on centers so that the total area occupied by the 96 stimulators is 6-7/8 by 4-3/8 inches. All of the electromagnetic valves are inside a pressurized box.

Figure A-4 shows the interior and Fig. A-5 shows the exterior of the tactile stimulator array. Small tubing is used to bring the airjets up to a top plate, where a variety of interjet spacings can be obtained. The height of the tubes above the plate can be adjusted to accommodate different body curvatures. Other arrangements are possible also. For example, the matrix can be split into two and each half placed near opposite sides of a body member such as the hand.

* The work reported in this appendix was supported under Contract NAS 2-1679.

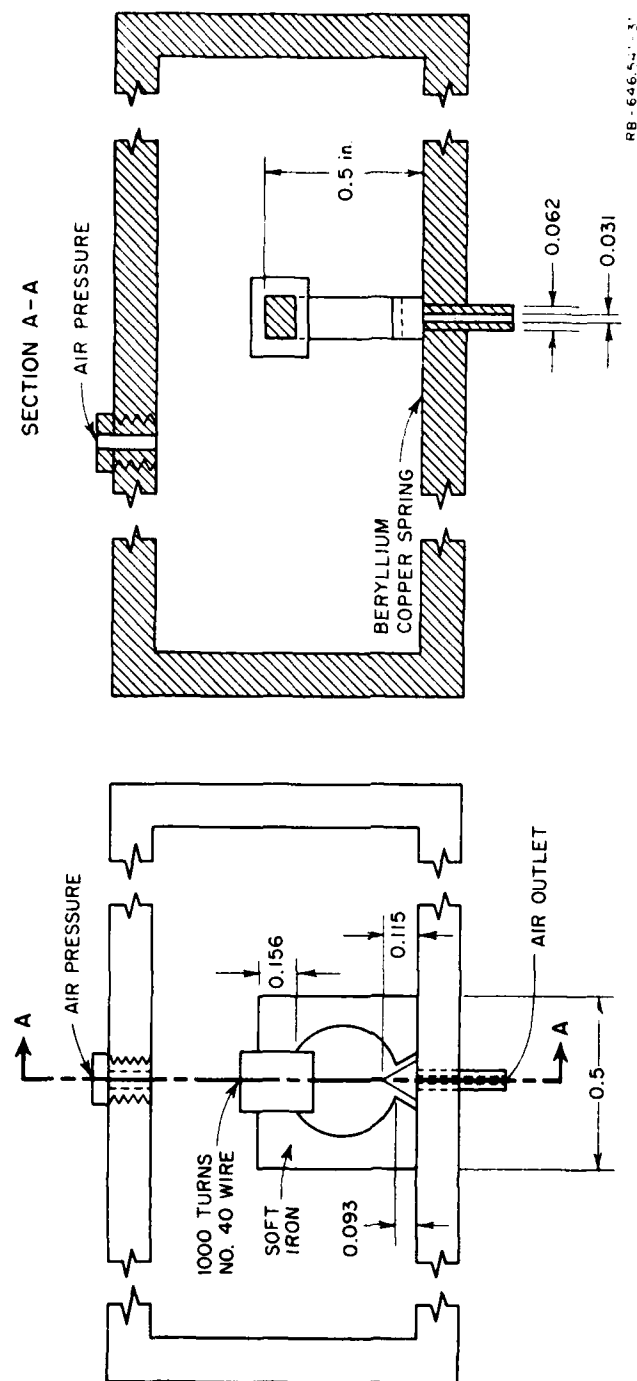


FIG. A-1 ELECTROMAGNETIC AIR VALVE

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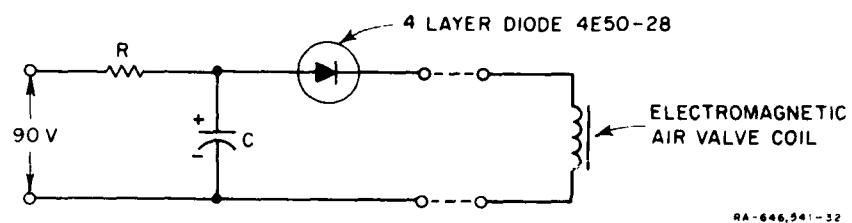


FIG. A-2 RELAXATION OSCILLATOR CIRCUIT
FOR THE ELECTROMAGNETIC AIR VALVE

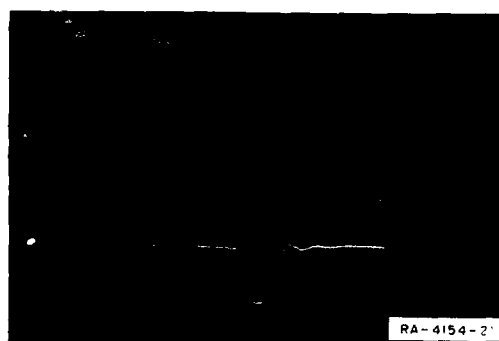
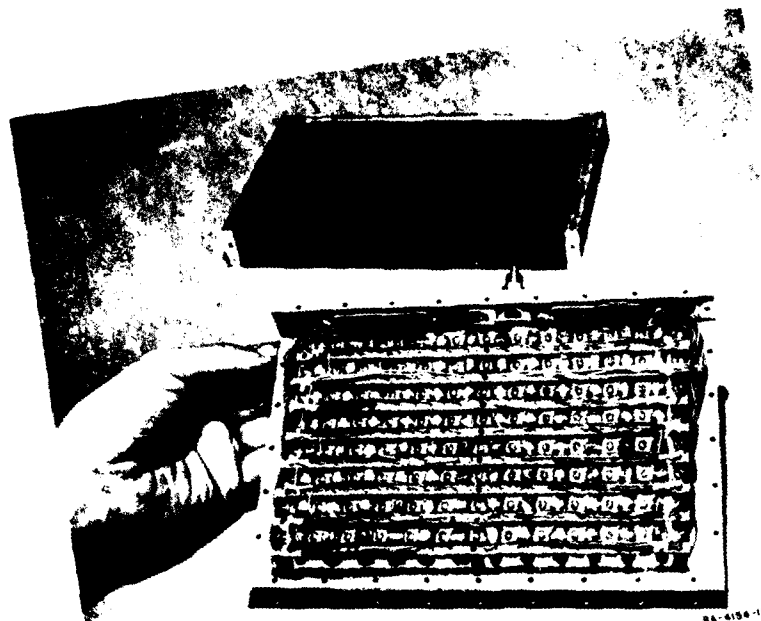


FIG. A-3 AIR PRESSURE MEASURED
1/8 INCH ABOVE AIRJET
STIMULATOR 1 (2.5 msec/cm)



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FIG. A-4 INTERIOR OF TACTILE DISPLAY CONSISTING OF 96 AIRJET STIMULATORS

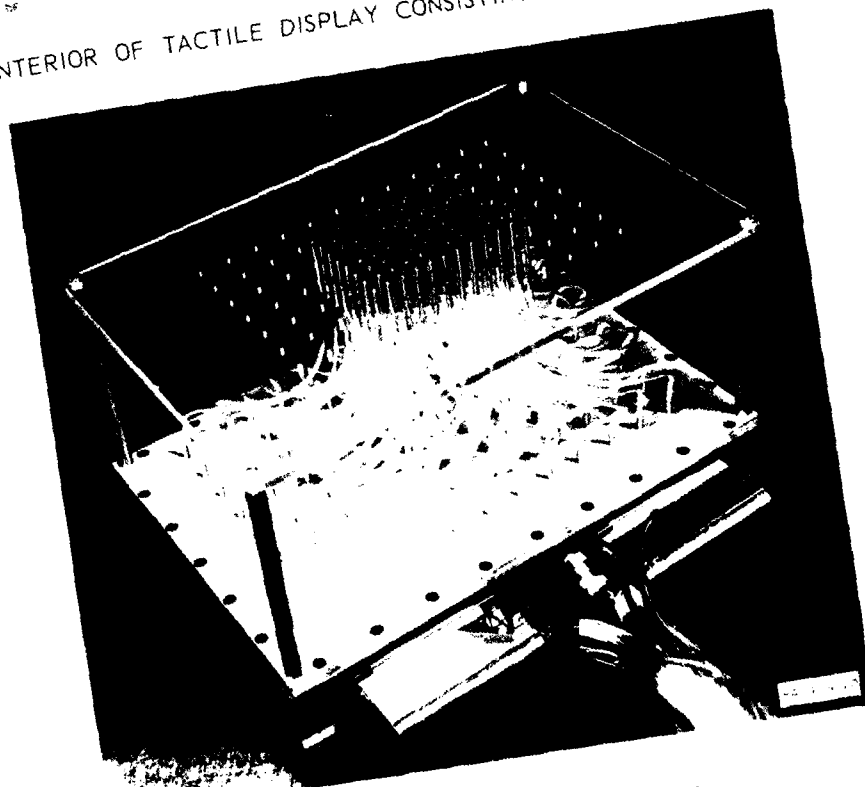


FIG. A-5 TACTILE DISPLAY UNIT

Appendix B
AIRJET ARRAY 2

Appendix B^{*}
AIRJET ARRAY 2

The valve operation of the first model airjet stimulator was marginal from the standpoint of complete cut-off of air flow when the valve was closed. It was felt that a better design could be made by using steel balls sliding in closely fitting holes. A first version of this jet design, which needed further improvement, is shown in Fig. B-1. In the position shown, the supply pressure is applied to both balls, and the space between them as well as the output port is exhausted to the atmosphere. There is a net force to the left, due to the different cross-sectional areas of the balls, which holds the valve closed. When the coil is energized, the larger ball is pulled to the right-hand end of its passage, allowing the smaller ball to move away from the supply port and across the output port. The air supply is thus led to the output, and the exhaust path is sealed off.

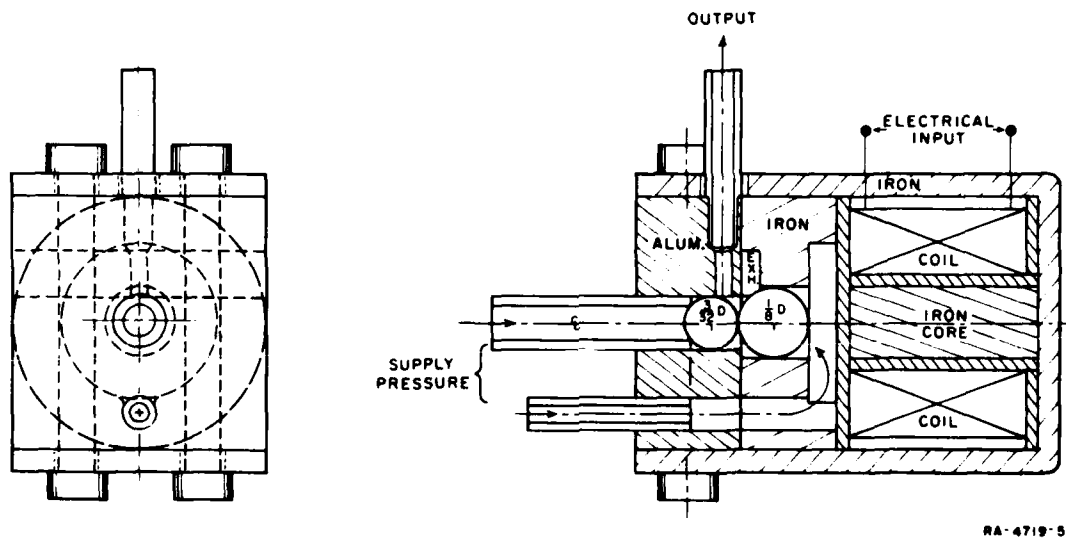


FIG. B-1 AIRJET TACTILE STIMULATOR

* The work reported in this appendix was supported under Contract NAS 2-1679.

An approximate analysis showed that the valve-closing force of 0.1 newtons from 10-psi air pressure could be overcome with the existing oscillator circuit and a coil of 1000 turns of No. 37 wire. An experimental model showed, however, that the magnetic circuit did not allow sufficient force to actuate the valve when the circuit was driven with the existing oscillator circuit, primarily because of eddy currents.

Several modifications were then made. The most significant was the use of a single ball, which reduces the mass of moving elements and simplifies construction. This, and a minor improvement in the magnetic circuit, produced a valve design that operates from the existing oscillator circuit and produces pulses up to 3 psi in amplitude from a 5-psi supply pressure. The pressure waveform is shown in Fig. B-2. A group of eight of these valves in a strip array with integral air passages and coils is shown in Figs. B-3 and -4. Twelve such strips were built to form an 8-by-12 array, which has operated very successfully.

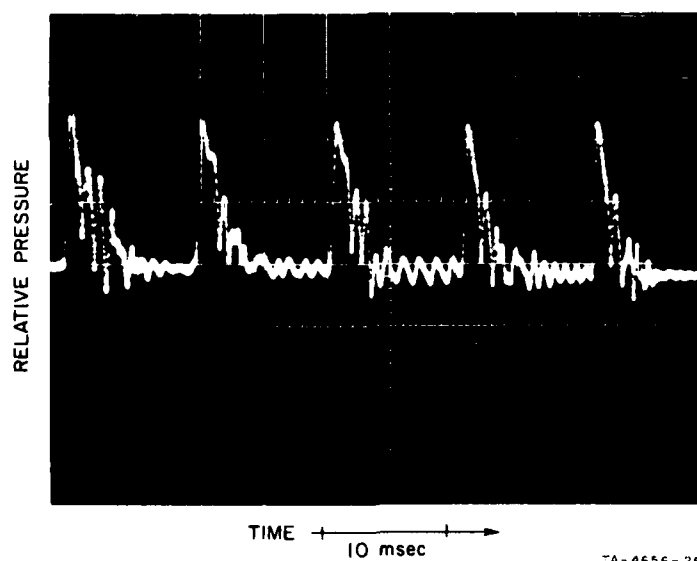
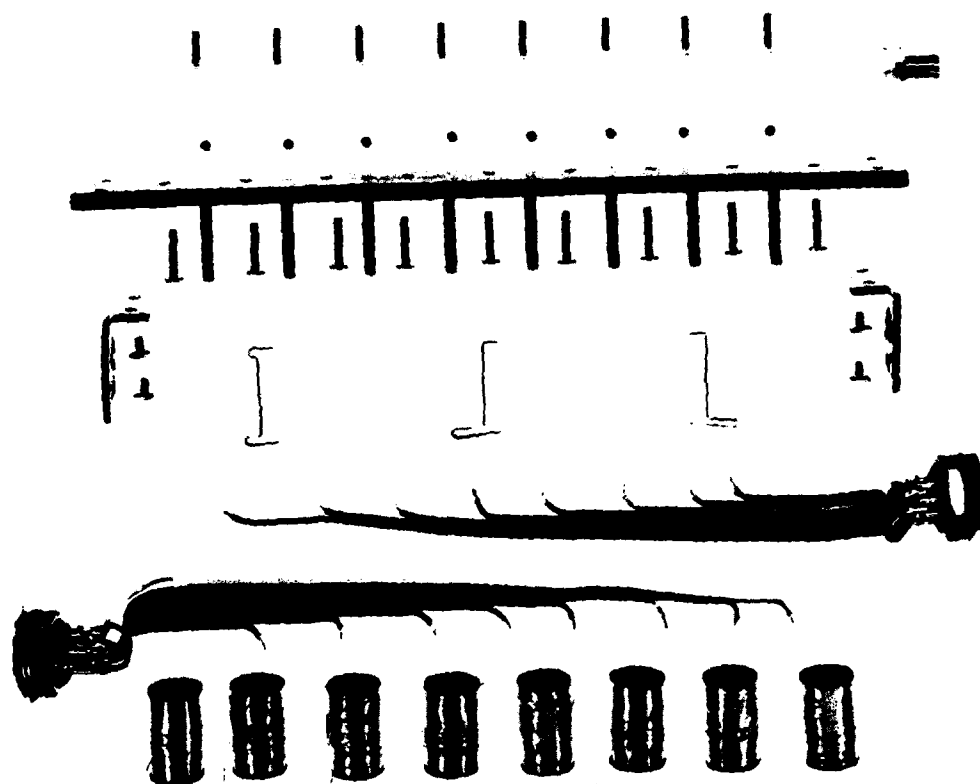


FIG. B-2 OUTPUT AIR PRESSURE PULSES FOR AIRJET STIMULATOR 2



RA-4719-43

FIG. B-3 EXPLODED VIEW OF ONE ROW OF AIRJET MATRIX

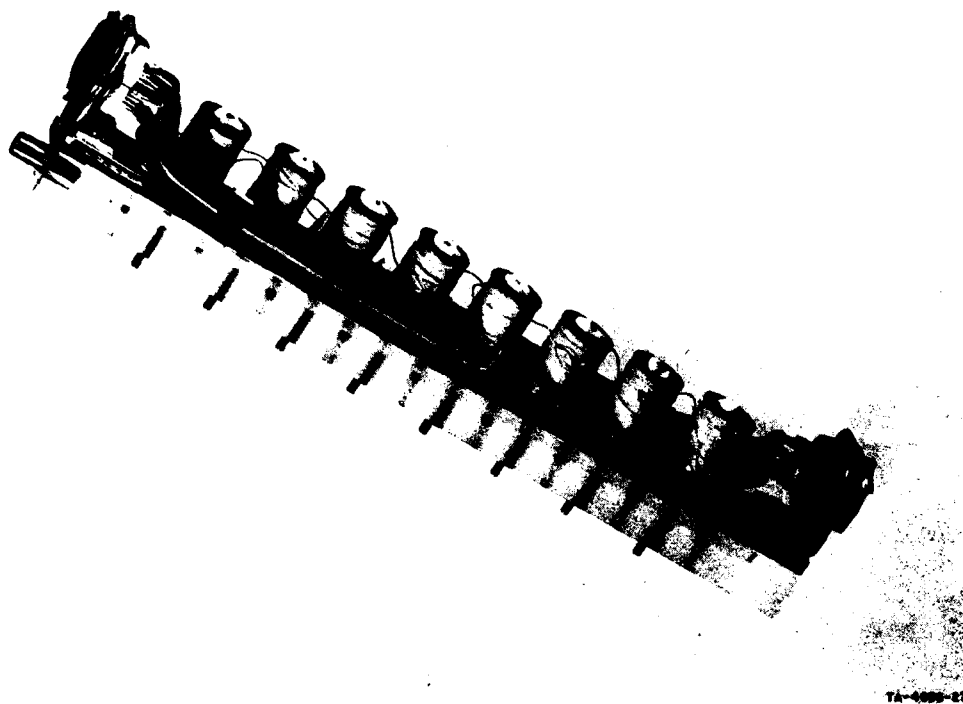


FIG. B-4 1-BY-8 AIRJET STIMULATOR ARRAY

Appendix C
BIMORPH ARRAY

Appendix C

BIMORPH ARRAY

A 12-by-8 piezoelectric bimorph array, Fig. C-1, built by Stanford University has been loaned to us for evaluation and comparison with the airjet array. In this array, the 96-lead zirconate bimorphs are cantilevered at 45 degrees from the base so that they vibrate like a reed. Rounded tips of 25-mil-diameter drill rods are attached with epoxy cement to the free ends of the bimorphs along a vertical axis, as suggested in Fig. C-2. The free tips are positioned so that they are flush with the top of the array of perforated holes in the horizontal plate. When the bimorphs are activated, the tips protrude through the perforations in the plate.

The bimorphs used are manufactured by the Clevite Corporation under the trade name PZT Bimorph. They are 1-1/2 inches long, 1/16 inch wide, and 24 mils thick. Each consists of a metallic center vane, on both sides of which oppositely polarized lead zirconate strips are attached. Outer surfaces, which are parallel to the center vane, are silver coated. The center vane is one electrode and the two outer surfaces, which are electrically connected to the mounting, are the second electrode. When a voltage is applied across the electrodes, the bimorph flexes by an amount proportional to the voltage and in a direction depending upon the polarity of the voltage. The tips of the bimorphs used deflect about 0.04 mils per volt.

Interface circuitry has been built so that this array can be operated from the same drive circuitry as the airjet array.

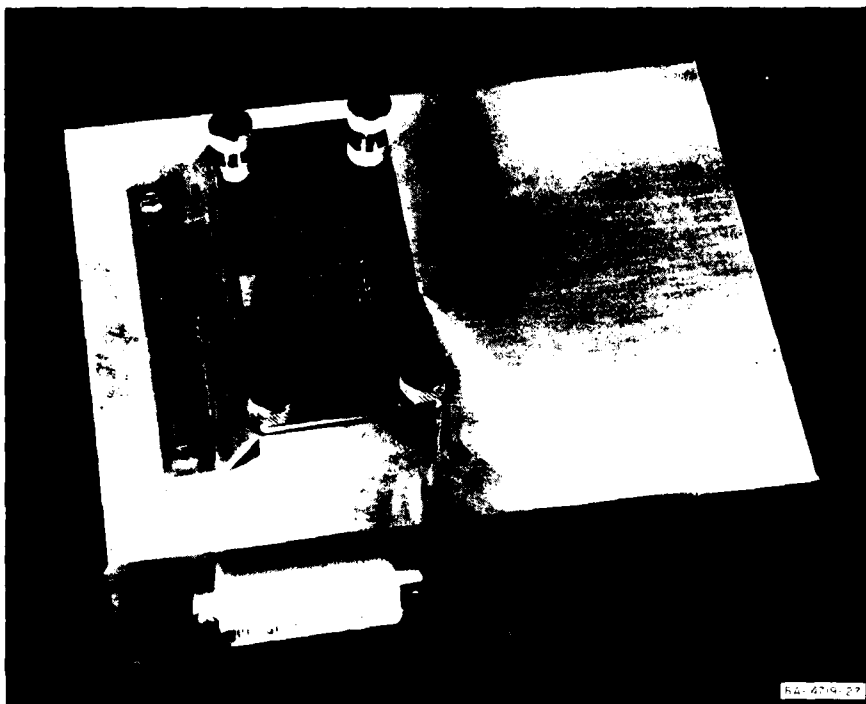


FIG. C-1 12-BY-8 BIMORPH STIMULATOR ARRAY

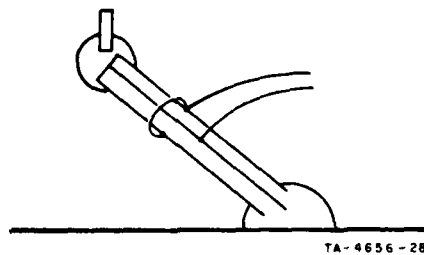


FIG. C-2 PHYSICAL ARRANGEMENT OF
A BIMORPH STIMULATOR

Appendix D
DIGITAL-COMPUTER-CONTROLLED SYSTEM

Appendix D*

DIGITAL-COMPUTER-CONTROLLED SYSTEM

1. General

Figure D-1 is a block diagram of the system that has been developed and assembled. The CDC 160-A computer is used in real time to store the stimulus patterns, scan them according to various temporal modes, output the scanned stimulus patterns, record and tabulate the subject's responses, and analyze the data. The timing for the stimulus presentation is controlled by an external clock. The control logic interfaces between the computer and a 12-by-8 storage matrix. The data in the storage matrix activates the tactile stimulators via the driver circuitry. An 8-by-12 light display is slaved to the tactual array. Each of these blocks is described below:

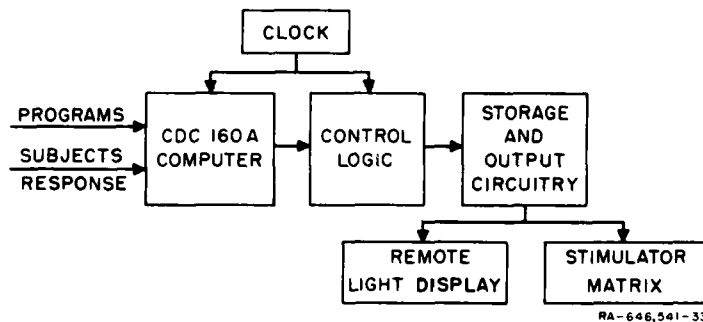


FIG. D-1 BLOCK DIAGRAM OF DIGITAL-COMPUTER-CONTROLLED SYSTEM

2. Computer

The CDC 160-A computer is a parallel, single-address electronic data processor. Operation is controlled by an internally stored program located in sequential addresses. The computer memory consists of two units (or banks) of magnetic core storage, each with a capacity of

* The work reported in this appendix was supported under Contract AF 33(615)-1099.

3. Control Logic

[illegible]

168

A sequence of operations is as follows: When the computer is ready to display a tactile pattern, it puts a signal on lines A, B, and C. A function-ready signal is then put on line T. The coincidence of these four signals sets control flip-flop (1). The output of this flip-flop, together with the clock signal, starts the shift register stepping through its nine steps.

The computer, 12.8 microseconds later, replaces the signals on Lines A, B, and C with a set of twelve binary signals on Data Lines A-L, which represents the first row of the output pattern. With the first ensuing clock pulse, an output-resume signal, S, is sent to the computer. This causes the computer to return an information-ready signal, R, assuming the Lines A-L have been properly set. Signal R opens gates on each of Channels A-L. These twelve signals, gated by the output of the first stage of the shift register, then energize the first row of twelve storage elements according to the 1's and 0's on the twelve computer data lines. The next clock pulse steps the shift register one position and sends an output-resume pulse to the computer.

The computer removes its information-ready signal, sets up a new data pattern on the twelve output lines, and then replaces its information-ready signal. This new data word is gated into the second row of the array storage. When no further data are to be displayed, the computer does not return an information-ready signal. The NOR gate (2) with neither S nor R present, resets flip-flop (1) and, via driver (3), resets the shift register. The system is now ready to restart on resumption of a function-ready signal and signals on Lines A, B, and C.

There is considerable flexibility in the manner in which a pattern can be scanned and reset. Different scan modes can be used by proper subroutine choice in the computer. Additional control is effected by manual switches in the control-logic section. There are three modes in which the control logic can be operated. In the first, called the frame-reset mode, selected stimulators are turned on a row at a time, until all eight rows have been energized. Then the entire frame is reset at once. A second, or line-reset mode turns on a row of the matrix and at the same

time resets one of the rows 2 to 8 behind, depending on the switch setting. Thus, at each clock step, one row is turned on and one row is turned off. In the third, or frame-presentation, mode the pattern from the computer is stored in the SCR matrix, and then the entire array of stimulators is activated simultaneously for a predetermined interval.

4. Storage and Output Circuitry

The storage section is activated by two sets of input (one from the twelve-line computer output and the second from the eight-line shift register output) that form an 8-by-12 matrix. Whenever the cross lines at any intersection point of the array are simultaneously excited a silicon-controlled rectifier (SCR) fires and remains energized. For example, whenever Stage 4 of the shift register and Line C of the computer output lines are both logic 1, the stimulator in position (4,3) in the 8-by-12 matrix is energized. The circuitry that fires the SCR is a transformer AND gate tailored to the two sets of input signals as shown in Fig. D-3. The reset circuitry is a transistor switch that controls the 90-volt stimulator supply. For as long as the SCR is fired, the corresponding relaxation oscillator circuit is energized and drives the airjet stimulator.

The state of each SCR is displayed on a 12-by-8 neon array. Each of these neons has an associated push button that can manually activate the relevant unit. This feature enables checkout of the system and presentation of special patterns.

5. Synchronized Output Circuitry

As described thus far, all of the 96 oscillators in the output are asynchronized. The system was originally built this way so that the frequency of each airjet could be different and frequency could be used as an information-bearing dimension. A difficulty with this system, however, is in making experiments on the effect of general change in frequency. For this purpose it is far easier to have all outputs derived from a single oscillator whose frequency and duty cycle can be varied. The original system has thus been augmented

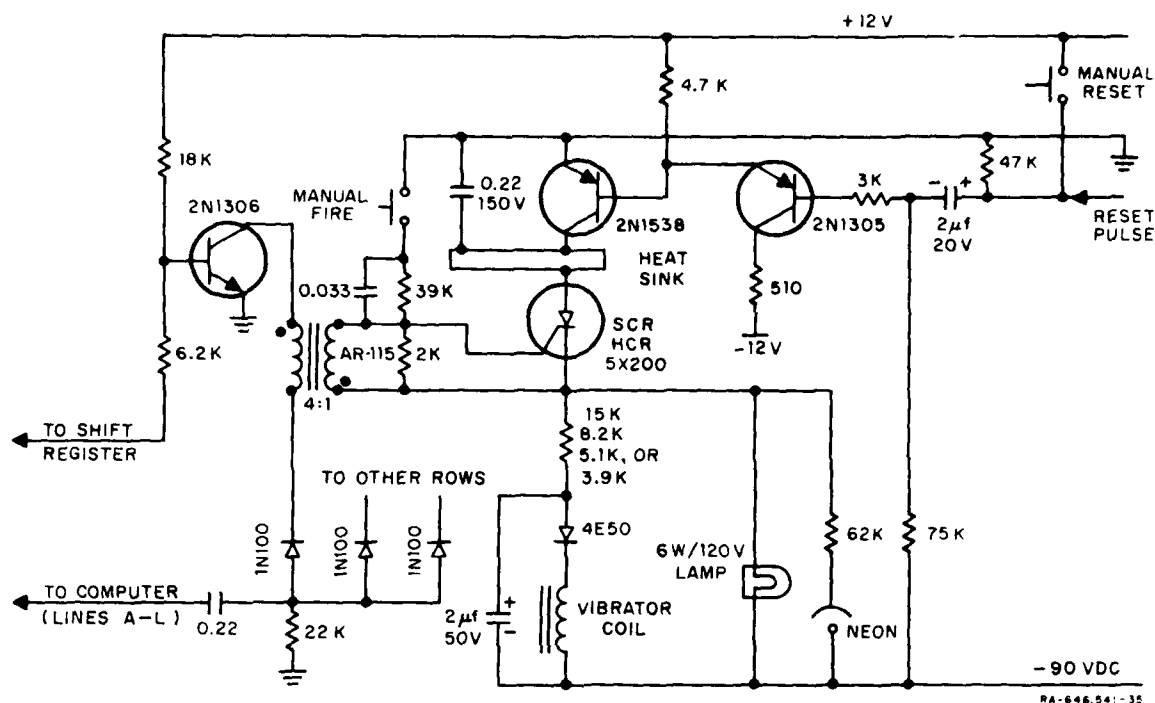
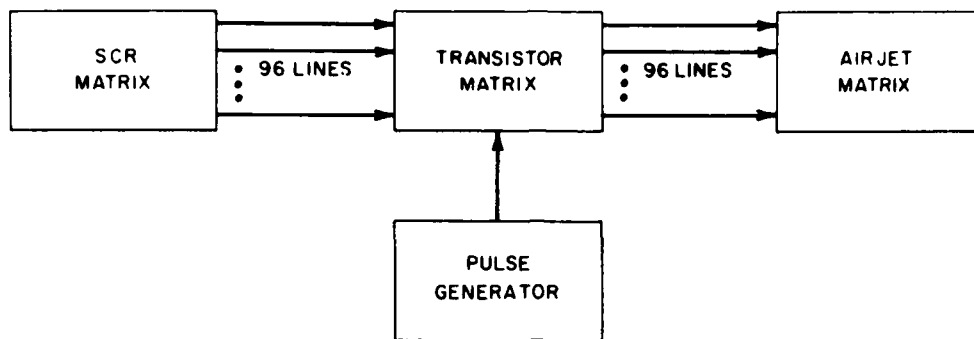


FIG. D-3 DRIVE CIRCUITRY FOR AIR VIBRATORS — SINGLE ELEMENT

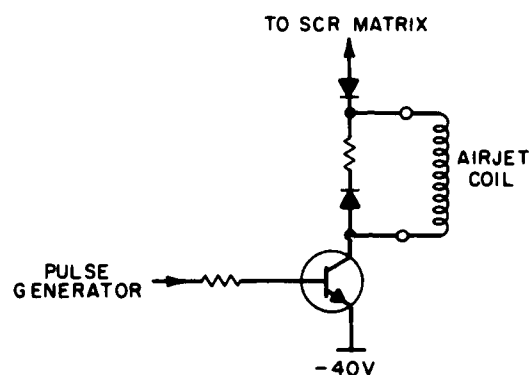
as shown in Fig. D-4 to incorporate an output display synchronously driven in this manner, although there still remains the facility to use the original type of display. (Only the Model 2 airjet system can be used in the synchronous mode, however, since it is necessary to have both ends of the drive coil electrically free, whereas in the first airjet construction, the array was constructed with one terminal of all jets in common.)

6. Subject Controls

Two controls have been added that have proven to be very useful for training and experimentation. One is a start-stop switch that allows the subject to stop and start the moving patterns. When this switch is in the stop position, a computer interrupt line is open-circuited so that the computer does not receive the pulse from the external equipment



(a) Block Diagram



(b) Circuitry for Single Airjet

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FIG. D-4 SYNCHRONOUS AIRJET STIMULATION SYSTEM

which signals it to continue the program. Also, when the switch is in the stop position, a battery is connected across an inductor. When the switch is thrown to the start position, the inductor is connected to the interrupt line, thereby generating a pulse that starts the program again.

The second control allows the subject to backspace a fixed number of patterns. This control operates by putting a pulse on a second computer interrupt line. When the computer receives this pulse, it subtracts five (for example) from the memory location stored in PTITL and returns to the program. Thus, the next pattern received by the subject is the fifth previous pattern, and the intervening pattern will be repeated.

7. Operation

In operation of this system two modes of timing have been used. In the first, shown in Fig. D-5, the computer is idle while the stimulus pattern is being displayed and the rate of stimulus presentation is controlled external to the computer. In the second mode, shown in Fig. D-6, the computer is performing the instructions specified by the stored program while the stimulus pattern is being displayed and the rate of stimulus presentation is controlled by the computer. Note that in the first timing mode there is a dead time equal to the length of time it takes the computer to execute the program. This mode is used when the dead time is not important for the particular experiment. For example, for the letter recognition experiments with the jittered array, external timing was important for self pacing so that the first mode was used. However, in the sessions on reading textual material, the dead time became appreciable around 30 wpm and the second mode was used.

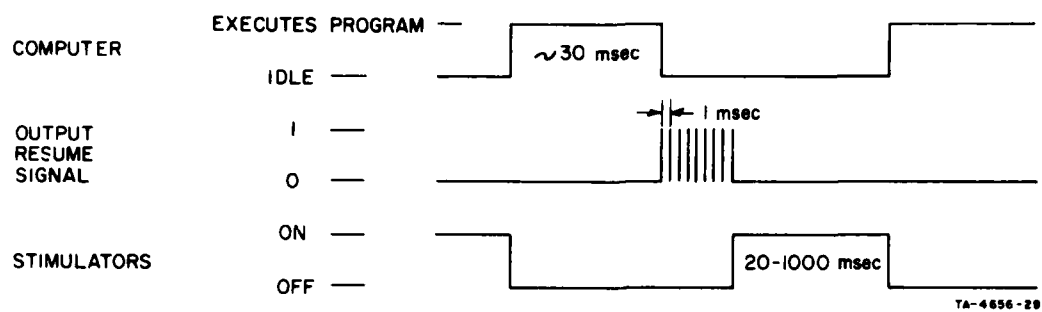


FIG. D-5 TIMING MODE 1

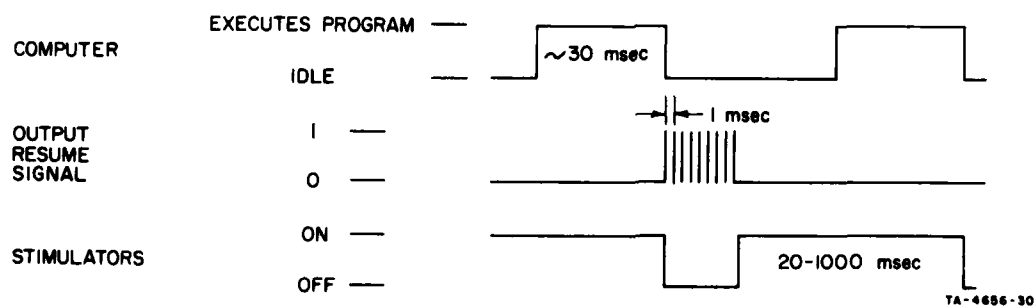


FIG. D-6 TIMING MODE 2

Appendix E
COMPUTER PROGRAMS

Appendix E*

COMPUTER PROGRAMS

Several programs have been developed for the CDC 160-A or CDC 160 computers for carrying out psychological experiments. These programs are described below.

1. Pattern Loader Program

The two-dimensional patterns that are to be displayed to the tactical sense are written in a format of a title followed by eight 4-digit octal numbers. These octal numbers specify which stimulators are activated (a 1 in the 12-digit binary number means that the stimulator corresponding to this 1 will be energized). For example, the pattern for activation of the matrix border is

BORD	TITLE
7777	
4001	
4001	
4001	
4001	data
4001	
4001	
7777	

The Pattern Loader Program takes the punched paper tape produced by typing the above format on the off-line Flexowriter, converts the data portion to binary, and stores the title and data in core locations starting at 1000. This routine also disregards blank tape, deletes, and carriage returns.

* The work reported in this appendix was supported by Contract AF 33(615)-1099.

2. Experiment Performance Program

This program has two modes of operation--a data input mode and a data output mode. In the input mode the program reads in, from either the paper tape reader or the typewriter, the sequence of patterns to be displayed. These pattern titles are stored until the memory is filled up and then the read-in operation is stopped. In the output mode this program takes each stored pattern title in turn, locates the pattern corresponding to the title, and then transfers control to one of the pattern scan programs.

3. Point Scan Program

When this program is used, the interface equipment is set so that each row of the stimulator matrix is reset before the new row is activated, one after the other:

(12,1), (12,2), (12,3), (12,4), (12,5), (12,6), (12,7), (12,8), (11,1), (11,2), ..., (1,8). After each point the matrix is reset; after 96 points, control is transferred to the Experiment Performance Program.

4. Line Scan Program

This program displays the pattern one row at a time from top to bottom. The interface equipment can be set so that three modes are possible with this program. In the first, called the frame-reset mode, selected stimulators are turned on a row at a time, until all eight rows have been energized. Then the entire frame is reset at once. A second, or line-reset mode turns on a row of the matrix and at the same time resets one of the rows 2 to 8 behind, depending on the switch setting. Thus, at each clock step, one row is turned on and one row is turned off. In the third, or frame presentation, mode the pattern from the computer is stored in the SCR matrix, and then the entire array of stimulators is activated simultaneously for a predetermined interval.

5. "Times Square" Pattern Scan Program I

This program moves a pattern across a 12-by-8 matrix from right to left in much the same manner as certain news display boards (e.g., as

in Times Square, New York City). Figure E-1 is a flow diagram for a part of this program. As shown, each line of the pattern is masked out except for the part to be displayed, then this line is shifted left (the left shift is an end-around shift) to the proper position. After all 8 lines of the pattern have been so shifted, the overall pattern has effectively been shifted by one column and the new shifted field is read out on the tactile stimulators.

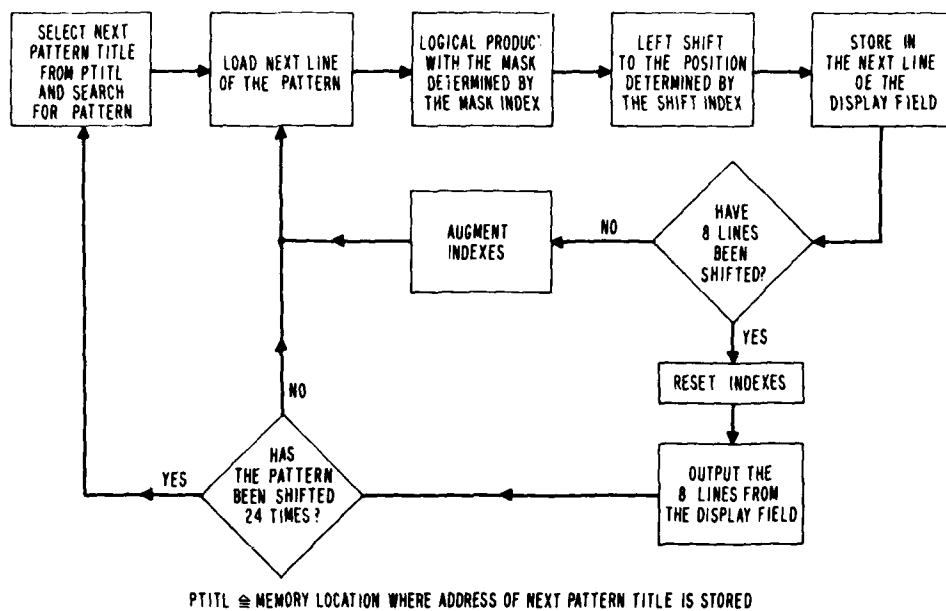


FIG. E-1 FLOW DIAGRAM FOR "TIMES SQUARE" COMPUTER PROGRAM

For the first frame presentation, all of the pattern except the left-most column is masked out and this column is shifted left once, with the result that it appears in the right-most column position of the display (since the left shift is an end-around shift). For the next frame presentation all but the two left-most columns are masked out and left-shifted twice so that they appear in the two right-most columns of the matrix. Since the matrix is 12 elements wide, it takes 24 single shifts to display a 12-column pattern in all possible positions. After 24 shifts the next pattern is selected and the process is repeated.

If letters are specified on a 5-by-8 matrix, two complete letters can be displayed simultaneously on the 12-by-8 array, with two empty columns between them. As a series of letters with this 7-column spacing is moved from right to left across the matrix, parts of three letters can be displayed at any one time. A display of this kind is very useful for studying information transmission with closely spaced letters, or any symbol set.

The flow diagram for the complete program is shown in Fig. E-2. As shown, three "Times Square" subroutines are used to operate on the three patterns that are in motion at any one time. Following through a sequence of operations, the first pattern is stored in "Times Square" Subroutine 2 and the first two patterns are shifted and read out 7 times. Next, the third pattern is stored in "Times Square" Subroutine 3 and all three patterns are shifted until the first pattern disappears off the left edge of the display. The process is repeated with the 4th, 5th, and 6th patterns.

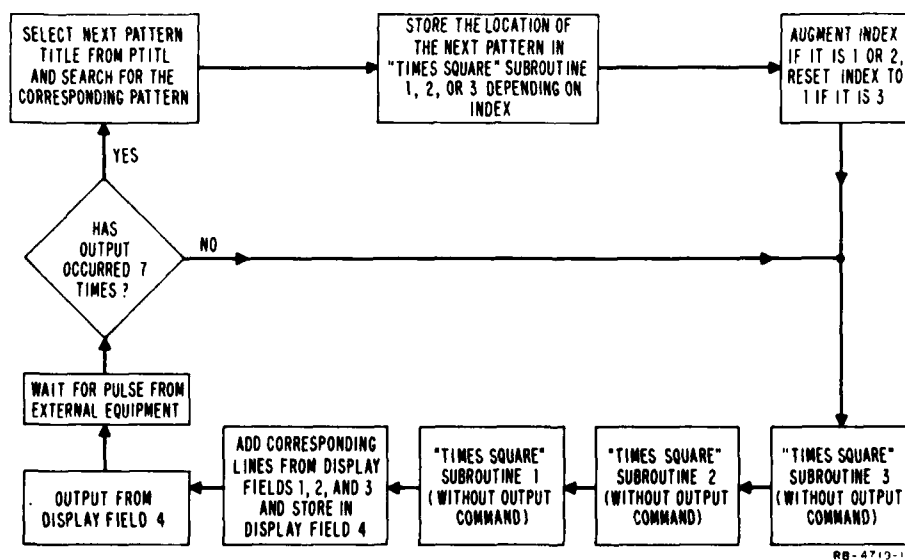


FIG. E-2 FLOW DIAGRAM FOR A "TIMES SQUARE" DISPLAY OF CLOSELY SPACED 7-BY-8 PATTERNS

6. "Times Square" Pattern Scan Program II

This program is similar to the Times Square Program I except that the patterns are moved across the 12-by-8 matrix from up to down instead of from right to left. The speed of the pattern movement is controlled by the computer instead of by the interface equipment. Since the pattern movement is in the same direction as the computer steps through its memory words, this program can operate at least twice as fast as "Times Square" Program I. Also, for alphabetic patterns, the stimulation arrays can be turned 90° to give the same right-to-left presentation as is possible with Times Square I.

7. Response-Recording Program

This routine records the subject's response (entered via a typewriter), compares it to the stimulus, and augments the proper location in the confusion matrix.*

8. Operation

These programs can be used together to perform a particular experiment. Figure E-3 illustrates how the Experiment Performance, Point Scan, Line Scan, and Subject Response Programs were combined to perform an experiment.

* Attneave (1959) is a convenient reference for confusion matrix representation and information analysis.

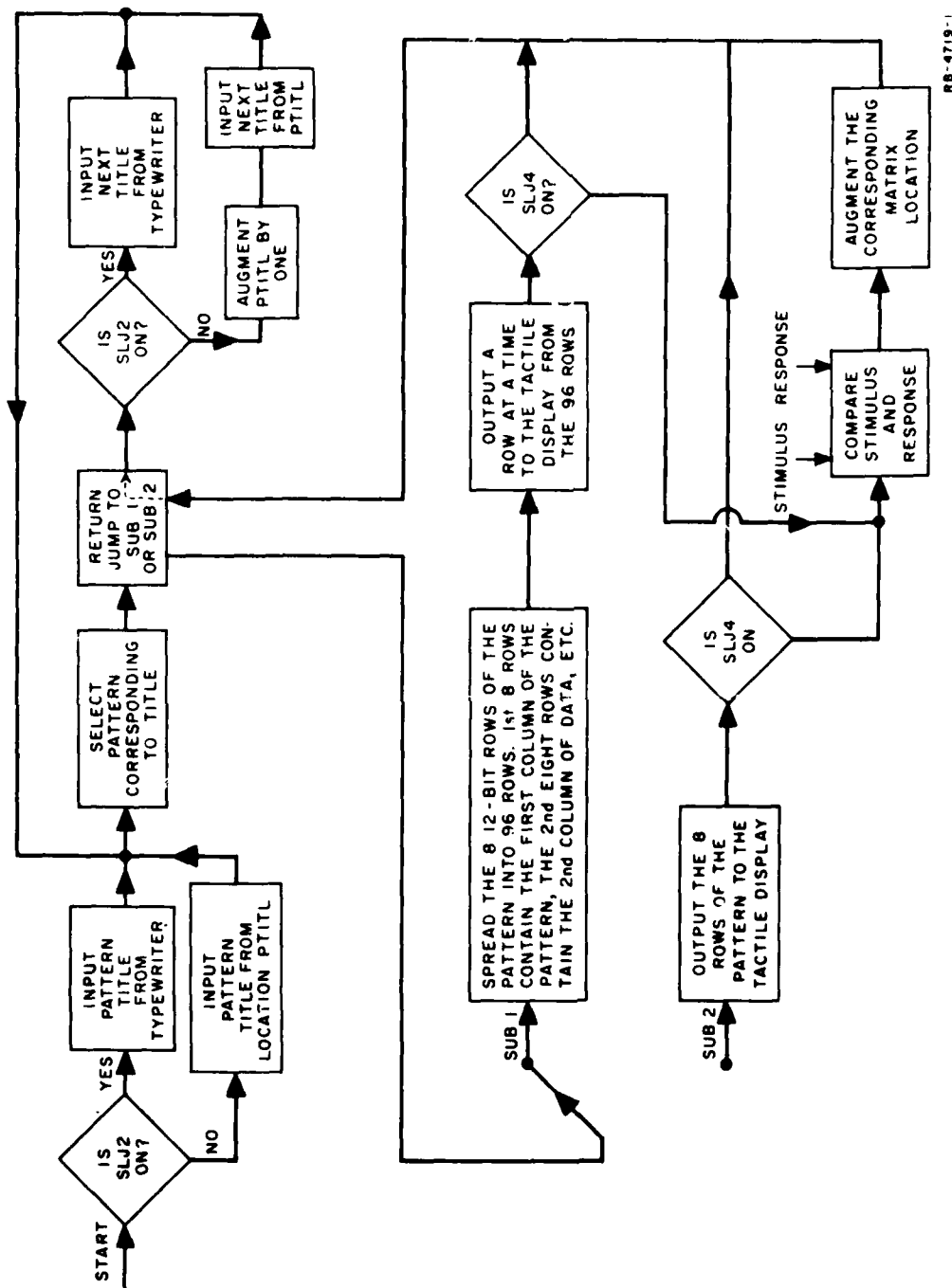


FIG. E-3 FLOW CHART FOR COMPUTER PROGRAMS

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Appendix F
TRACKING SYSTEM 1

Appendix F*

TRACKING SYSTEM 1

1. Compensatory Tracking

The system of Fig. F-1 has been developed, allowing us to use the 12-by-8 stimulus array, together with its associated circuitry, to perform two-dimensional compensatory tracking experiments. Since a square array of stimulators is appropriate, and since the center of the array was chosen as zero error (implying an odd number of stimulators), the tracking display actually uses only a 7-by-7 portion of the 12-by-8 array of stimulators.

An appropriate command signal, consisting of x and y coordinates, is generated by several operational amplifiers in the Donner analog computer. The subject of the experiment attempts to follow the command signal by manually operating an x-y control stick. The difference between the command signal and the signal from the x-y control stick is presented to the subject via a 7-by-7 airjet matrix.

The analog computer takes the difference between the command signal and the signal from the control stick for both the x and y components. The x error signal and the y error signal are sent to a parallel group of amplitude gates and time-sampling gates. The amplitude gates classify the x error signal and the y error signal into one of seven appropriate levels corresponding to the 7-by-7 airjet matrix. The sampling-rate multivibrator is set to operate at approximately five samples per second. It drives the sampling gate multivibrator which in turn operates the time-sampling gates. The time-sampling gates are attached to the output of each of the amplitude gates. Thus, the output of the x and y amplitude gates are sampled five times per second, and this x and y information is used to turn on the appropriate airjet in the matrix corresponding

* The work reported in this appendix was supported under Contract NAS 2-1679.

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Appendix F^{*}
TRACKING SYSTEM 1

1. Compensatory Tracking

The system of Fig. F-1 has been developed, allowing us to use the 12-by-8 stimulus array, together with its associated circuitry, to perform two-dimensional compensatory tracking experiments. Since a square array of stimulators is appropriate, and since the center of the array was chosen as zero error (implying an odd number of stimulators), the tracking display actually uses only a 7-by-7 portion of the 12-by-8 array of stimulators.

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The analog computer takes the difference between the command signal and the signal from the control stick for both the x and y components. The x error signal and the y error signal are sent to a parallel group of amplitude gates and time-sampling gates. The amplitude gates classify the x error signal and the y error signal into one of seven appropriate levels corresponding to the 7-by-7 airjet matrix. The sampling-rate multivibrator is set to operate at approximately five samples per second. It drives the sampling gate multivibrator which in turn operates the time-sampling gates. The time-sampling gates are attached to the output of each of the amplitude gates. Thus, the output of the x and y amplitude gates are sampled five times per second, and this x and y information is used to turn on the appropriate airjet in the matrix corresponding

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to the x and y value of the error signal at that time. The sampling rate multivibrator also triggers a delay multivibrator that is set for approximately 100 milliseconds. At the end of the 100-msec delay, this multivibrator then pulses the center airjet in the matrix.

Thus, the magnitude and direction of the vector representing the error signal are coded into the sequential pulsing of the two airjets--one, the airjet whose location is determined by the x and y value of the error signal; and two, a reference airjet located in the center of the matrix. Thus, the error vector, whose magnitude and direction can be sensed as an apparent-motion line, points in the direction in which the subject should move the control stick in order to reduce the error to a minimum. Since the airjets are operated by silicon controlled rectifiers, they require a reset pulse after each firing. A delay multivibrator and driver also driven by the sampling-rate multivibrator provides this function.

Most of this circuitry is standard and is therefore not shown in detail. However, the amplitude gate circuitry may be of some interest since the amplitude gates and time-sampling gate circuitry are integrated into one circuit. Figure F-2 shows the detailed circuitry for the three gate levels and the time-sampling gates for the +x section. The +y section is identical to this, and the -x and -y circuits are identical except that all voltages are inverted, diode orientation is reversed, and the transistors are counterparts (pnp is substituted for npn and vice versa). Not shown on the schematic is the necessary pulse-inverting circuit for the negative counterparts (required to provide a standard pulse polarity to drive the SCR circuitry associated with the airjet matrix).

2. Pursuit Tracking

To permit pursuit tracking experiments, switching gates are inserted into the input lines to the x and y drivers. The function of these gates is to permit the inputs to the amplitude-quantizing gates to be alternately switched between two sources. In synchronism with switching between the two input sources (presently at a 5-cps rate), the frequency

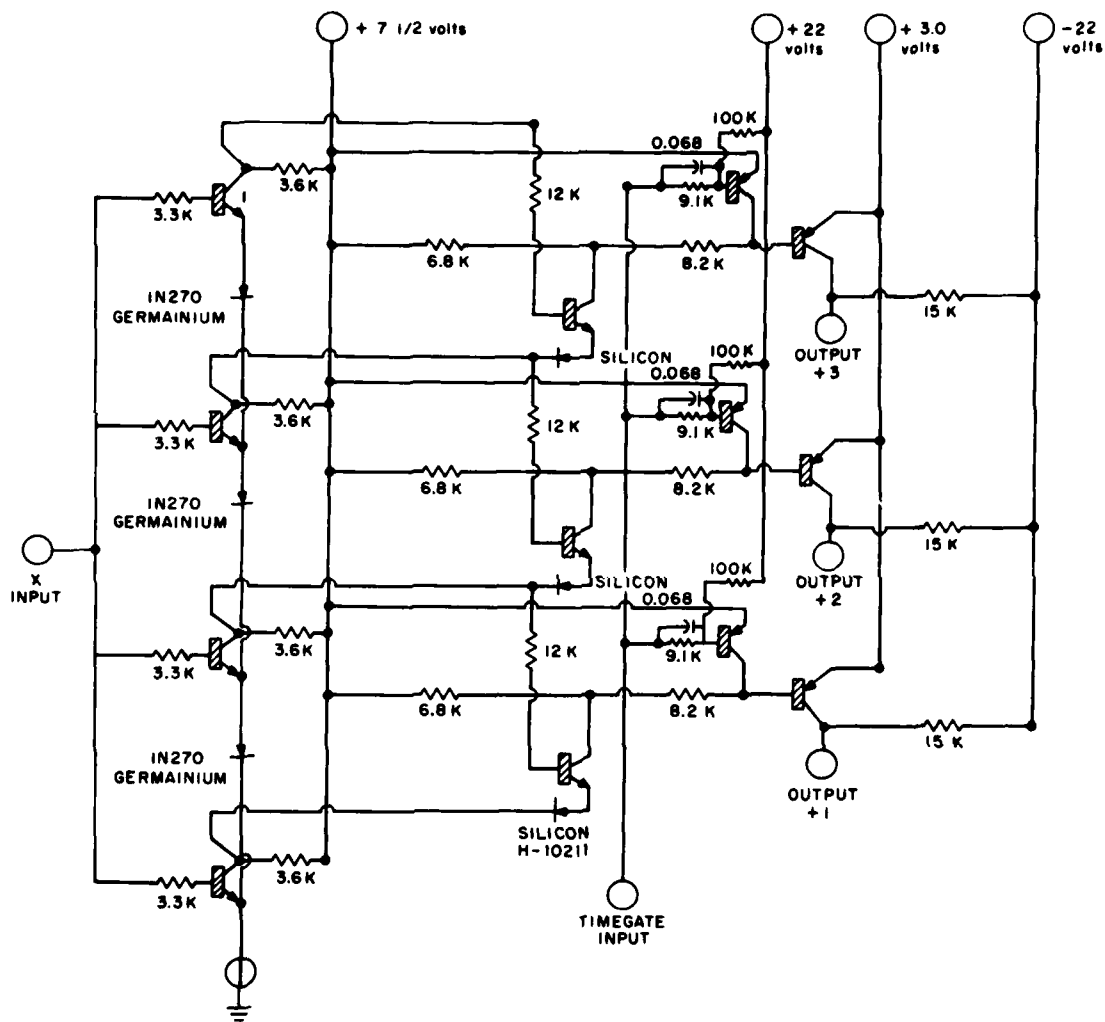


FIG. F-2 AMPLITUDE GATE CIRCUITRY

at which the selected airjet is pulsed is alternated between two selected values (presently 30 cps and 90 cps). This frequency difference allows the subject to determine which of the two inputs is being displayed. Thus two stimulators are alternately energized on the airjet matrix. Their position in the matrix indicates the (x,y) values of the two pairs of input signals and the airjet pulsation frequency indicates which pair is being displayed. The airjet in the center of the matrix (i.e., reference) is no longer driven from a special circuit but is driven as a normal part of the matrix.

With this modification compensatory tracking is achieved singly by connecting one pair of input signals of the switching gate to the error signal and the other pair to fixed dc values. For pursuit tracking one input pair is connected to the response signal. Thus, the airjet matrix can display both the desired position and the actual position.

Appendix G
TRACKING SYSTEM 2

Appendix G*
TRACKING SYSTEM 2

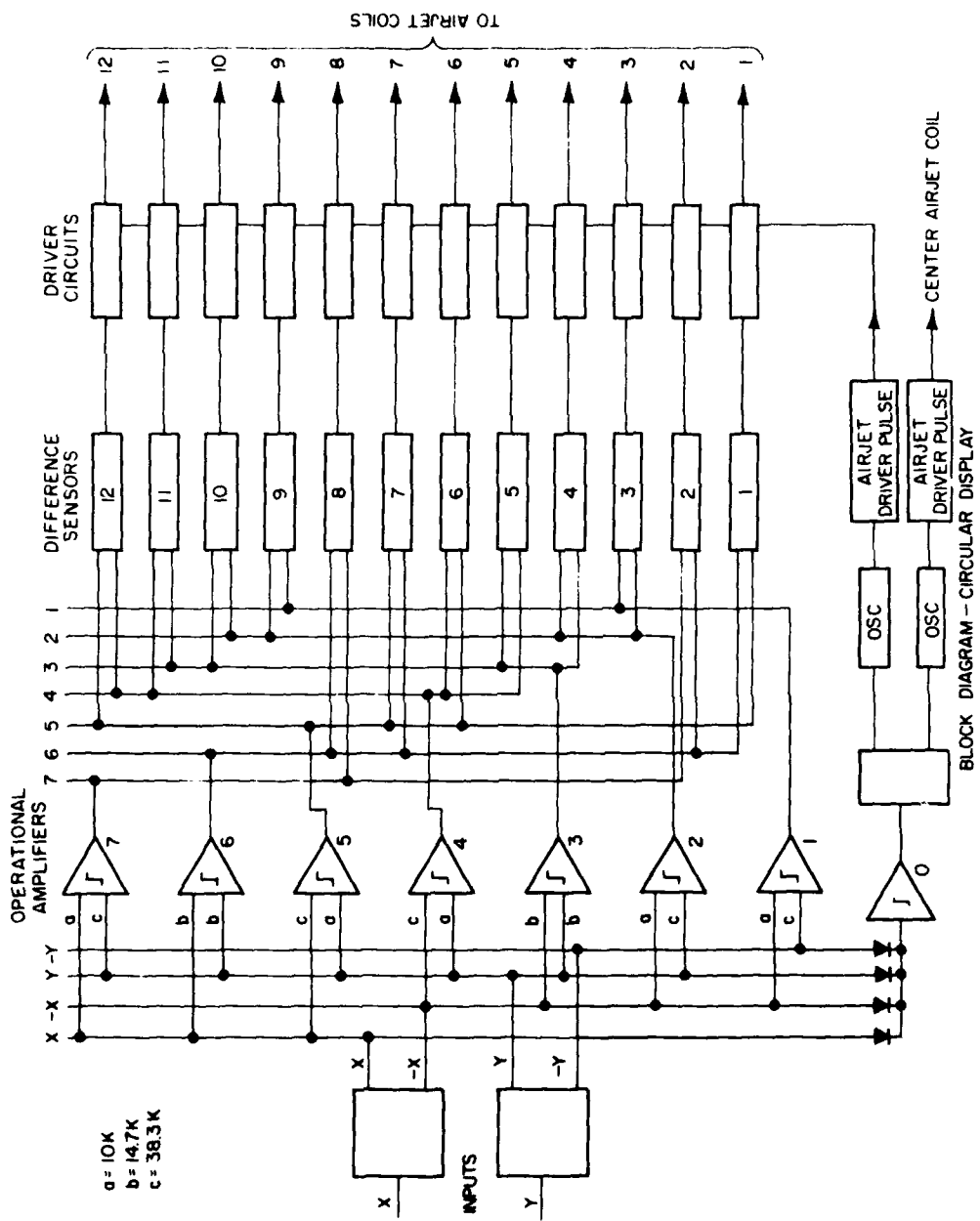
The good results from tracking experiments with high display gain led us to consider a relatively simple two-dimensional tracking display consisting simply of a single ring of twelve stimulators, with a single reference stimulator in the center. To adapt the x,y error data from the analog computer for this display the special circuitry of Fig. G-1 was built. If an error vector lies anywhere within a particular radial sector, and the error is larger than a given magnitude, then the single stimulator corresponding to this radial zone is activated. Twelve 30-degree-wide zones are defined by six lines through the origin. To determine just which of the twelve zones an error lies in, the dot product is formed between the error vector and each of the six lines that pass through the origin. Each line can simply be defined by a single slope or angle.) Each dot product consists then of multiplying the error coordinates (x,y) by a proper sine and cosine. This is the significance of the three weighting numbers, a, b, and c, beside each input to the column of operation amplifiers. (The seventh amplifier is simply to obtain a negative version of the first amplifier.) The three values a, b, and c, are input resistance values, corresponding to inverse sines, respectively of 15, 45, and 75 degrees, multiplied by 100K. Each operational amplifier has a feedback resistor $R = 100K$. Thus the equation for the first amplifier is simply

$$\frac{E_{out}}{R} = \frac{x}{a} + \frac{y}{b}$$

or

$$E_{out} = x \sin \theta + y \cos \theta, \quad \text{for } \theta = 15 \text{ degrees}.$$

* The work reported in this appendix was supported under Contract NAS 2-1679.



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FIG. G-1 SYSTEM FOR TWO-DIMENSIONAL TRACKING

Each amplifier contains a positive and negative limiter, so the output from each amplifier is either a large positive or a large negative value, depending on whether the projection of the error vector on the particular radial is positive or negative. The function of the second column of logic elements is to determine in which zone the projection polarity changes. There will be two such zones but the polarity of the change is always different for the two zones. The logic circuitry detects both the presence and the magnitude of the change, and thus one unique zone is determined for each input sector--the selected zone is geometrically 90 degrees displaced from the error sector, but nevertheless the assignment is unique. Figure G-2 illustrates the input signal zones that produce separate tactile outputs.

The lower circuitry in the figure is used to control whether excitation is on the ring, for error larger than a certain magnitude, or whether the center stimulator is excited for smaller error.

This circuitry is easily converted--by simply shifting about a half dozen wires--to a one-dimensional linear display containing 13 stimulators, one center stimulator and six on either side. The arrangement for one-dimensional display is shown in Fig. G-3. In this case the input error signal (3) is simply plus or minus. A second set of input lines connect to the operational amplifiers. The input resistors from the right-hand line are all equal. The input resistors from the left-hand line increase progressively from stage to stage. The right-hand line is clamped to a plus or minus voltage depending on the polarity of error. For any given magnitude of error, the left-hand inputs of some of the operational amplifiers will surpass the clamp (reference) voltage of the right-hand line,

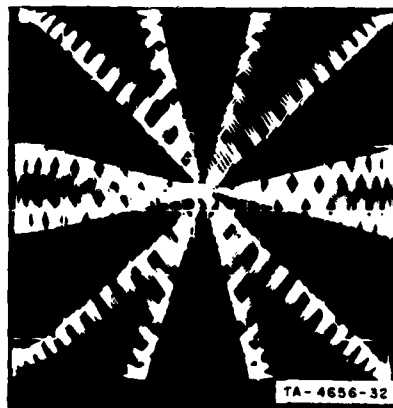
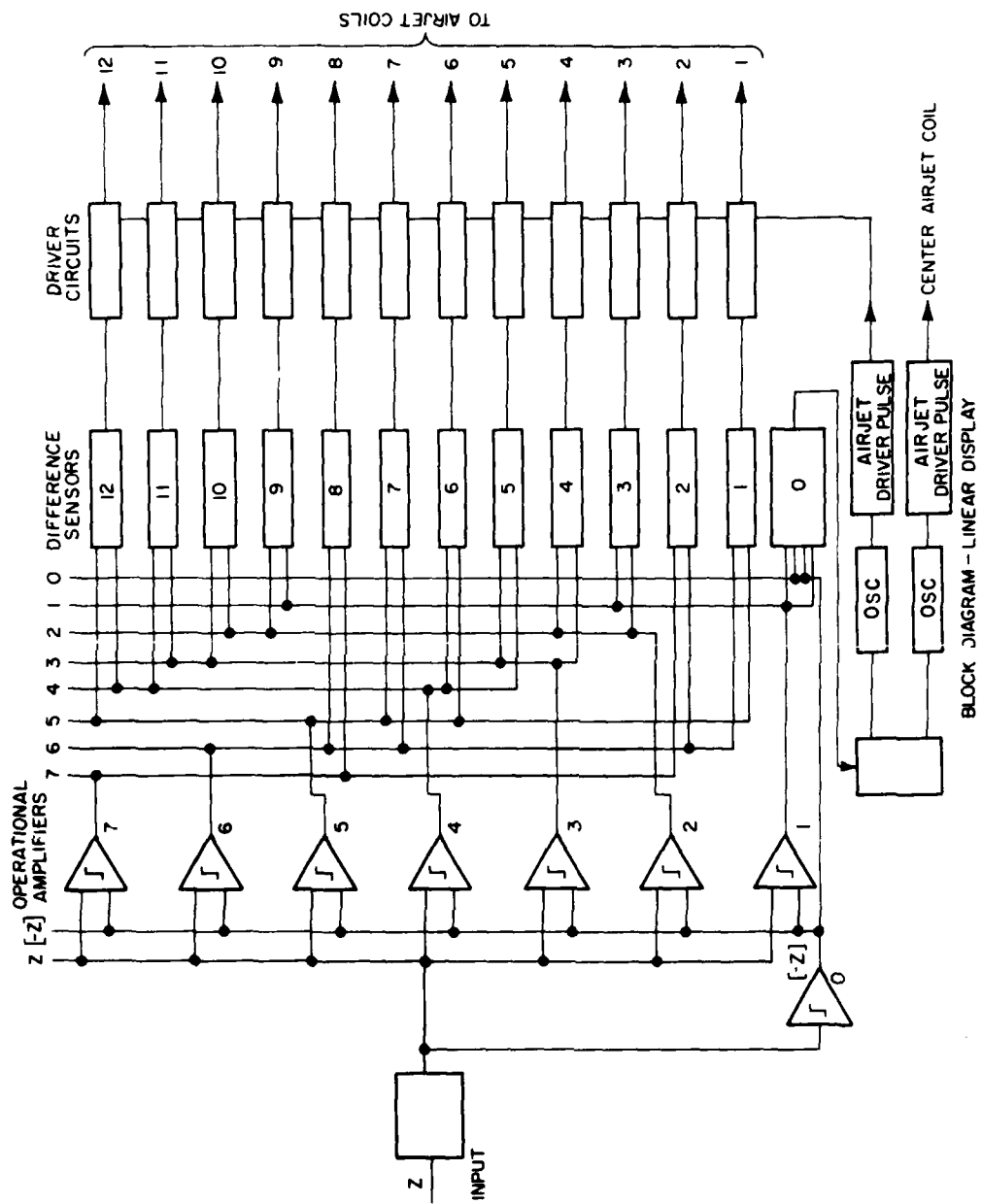


FIG. G-2 ZONES ILLUSTRATING THE OPERATION OF THE TWO-DIMENSIONAL RING TRACKING DISPLAY



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FIG. G-3 SINGLE-AXIS MODE FOR SYSTEM OF FIG. G-1

and some will not. As the magnitude of error changes, the position of the polarity transition will shift. The transition position is monitored by the second column of amplifiers, as in the radial mode of operation. For small error the outputs from the twelve stimulators are gated off and the center stimulator is energized.

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